

AD-A246 314



2

**NAVAL POSTGRADUATE SCHOOL**  
**Monterey, California**



**DTIC**  
**ELECTE**  
**FEB 21 1992**  
**S B D**

**THESIS**

**STUDY OF THE TRANSITION TO TURBULENCE  
WITHIN A CURVED RECTANGULAR CHANNEL  
WITH 40 TO 1 ASPECT RATIO**

by

Steven J. Fuqua

September 1991

Thesis Advisor:  
Thesis Co-Advisor:

Phillip M. Ligrani  
Chelakara S. Subramanian

Approved for public release; distribution is unlimited.

92 2 19 081

**92-04328**



Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

## REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Naval Postgraduate School	6b. OFFICE SYMBOL (If Applicable) 34	7a. NAME OF MONITORING ORGANIZATION Naval Postgraduate School			
6c. ADDRESS (city, state, and ZIP code) Monterey, CA 93943-5000		7b. ADDRESS (city, state, and ZIP code) Monterey, CA 93943-5000			
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Propulsion Directorate	6b. OFFICE SYMBOL (If Applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER  MIPR C-30030-P			
8c. ADDRESS (city, state, and ZIP code) US Army Aviation R/T Act. AVSCOM NASA-Lewis; Cleveland, OH 45433		10. SOURCE OF FUNDING NUMBERS			
		PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
11. TITLE (Include Security Classification) STUDY OF THE TRANSITION TO TURBULENCE WITHIN A CURVED RECTANGULAR CHANNEL WITH 40 TO 1 ASPECT RATIO					
12. PERSONAL AUTHOR(S) Fuqua, Steven Jay					
13a. TYPE OF REPORT Master's Thesis	13b. TIME COVERED FROM 1/91 TO 9/91	14. DATE OF REPORT (year, month, day) September 1991	15. PAGE COUNT 178		
16. SUPPLEMENTARY NOTATION The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.					
17. COSATI CODES			18. SUBJECT TERMS (continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUBGROUP	Dean vortices, centrifugal instabilities, turbulence, rectangular curved channel, laminar/turbulent transition		
19. ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>Longitudinal turbulence intensity and streamwise mean velocity variations are studied from measurements using single-sensor hot-wire probes at Dean numbers from 50 to about 450 in a curved rectangular channel with 40 to 1 aspect ratio, mild curvature, and an inner to outer radius ratio of 0.979. Measured results show significant increases in the longitudinal turbulence intensity as the Dean number increases above 150. These increases are first apparent near the concave surface in upwash regions between individual vortices which make up each vortex pair. Such increases correspond closely with twisting vortex motions, which is important in regard to transition from laminar to turbulent flow because these variations provide evidence that twisting results in the first important increases in turbulence energy at a given location as the Dean number increases.</p>					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL Professor Ligrani			22b. TELEPHONE (Include Area Code) (408) 646-3382	22c. OFFICE SYMBOL	

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted

SECURITY CLASSIFICATION OF THIS PAGE

All other editions are obsolete

Unclassified

Approved for public release; distribution is unlimited.

**Study of the Transition to Turbulence  
Within a Curved Rectangular Channel  
with 40 to 1 Aspect Ratio**

by

**Steven Jay Fuqua  
Lieutenant, United States Navy  
B.S., Tennessee Technological University, 1984**

Submitted in partial fulfillment of the  
requirements for the degree of

**MASTER OF SCIENCE IN MECHANICAL ENGINEERING**

from the

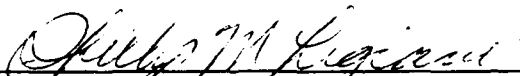
**NAVAL POSTGRADUATE SCHOOL**

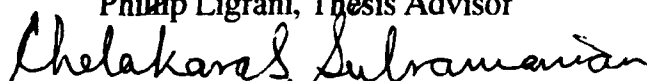
September 1991

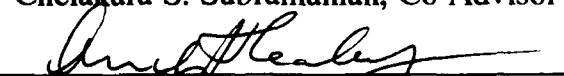
Author:

  
Steven J. Fuqua

Approved by:

  
Phillip Ligrani, Thesis Advisor

  
Chelakara S. Subramanian, Co-Advisor

  
Anthony J. Healey, Chairman  
Department of Mechanical Engineering

## ABSTRACT

Longitudinal turbulence intensity and streamwise mean velocity variations are studied from measurements using single-sensor hot-wire probes at Dean numbers from 50 to about 450 in a curved rectangular channel with 40 to 1 aspect ratio, mild curvature, and an inner to outer radius ratio of 0.979. Measured results show significant increases in the longitudinal turbulence intensity as the Dean number increases above 150. These increases are first apparent near the concave surface in upwash regions between individual vortices which make up each vortex pair. Such increases correspond closely with twisting vortex motions, which is important in regard to transition from laminar to turbulent flow because these variations provide evidence that twisting results in the first important increases in turbulence energy at a given location as the Dean number increases.

<b>Accession For</b>	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

## TABLE OF CONTENTS

I.	INTRODUCTION .....	1
A.	BACKGROUND.....	1
B.	OBJECTIVES .....	3
C.	ORGANIZATION .....	3
II.	EXPERIMENTAL APPARATUS.....	4
A.	CURVED CHANNEL.....	4
1.	Description of the Facility .....	4
2.	Cleaning the Channel.....	5
B.	PROBES, ELECTRONICS AND DATA ACQUISITION SYSTEM.....	5
1.	Hot-wire Probes.....	6
2.	Hot-wire Anemometer Bridge.....	6
3.	Signal Conditioner.....	7
4.	Analog-to-Digital Converter.....	7
5.	Microcomputer.....	8
6.	Temperature Measurement.....	8
C.	PROBE TRAVERSING DEVICES.....	9
1.	Survey Apparatus.....	9
2.	Near Wall Apparatus .....	9
III.	EXPERIMENTAL PROCEDURES.....	11
A.	HOT-WIRE CALIBRATION.....	11
B.	DEAN NUMBER DETERMINATION .....	12
C.	MEASUREMENT OF DEAN NUMBER SURVEYS .....	12
1.	Procedures.....	12

2.	Data Reduction.....	14
a.	Calculation of Turbulence Statistics .....	14
b.	Temperature Drift Correction.....	15
D.	PROCEDURES FOR MEASUREMENT OF NEAR WALL PROFILES .....	16
IV.	EXPERIMENTAL RESULTS .....	18
A.	INLET TURBULENCE INTENSITY .....	18
B.	SURVEYS.....	19
1.	Normalized Streamwise Mean Velocity.....	20
2.	Velocity Perturbation.....	21
3.	Longitudinal Reynolds Normal Stress .....	23
C.	NEAR WALL PROFILES.....	26
1.	Streamwise Mean Velocity .....	26
2.	Longitudinal Reynolds Stress.....	29
C.	EFFECT OF CHANNEL CLEANING .....	30
V.	SUMMARY AND CONCLUSIONS.....	32
	APPENDIX A. FIGURES .....	34
	APPENDIX B. SOFTWARE DIRECTORY.....	153
	APPENDIX C. DATA DIRECTORY.....	155
	LIST OF REFERENCES.....	160
	INITIAL DISTRIBUTION LIST.....	163

## LIST OF FIGURES

Figure 1.	Schematic of Test Facility.....	35
Figure 2.	Test Facility (Side View).....	36
Figure 3.	Details of Test Section.....	37
Figure 4.	Schematic of Support Block .....	38
Figure 5.	Detail of Support Block and Probe Mount Assembly.....	39
Figure 6.	Data Acquisition System .....	40
Figure 7.	Single-sensor Hot-wire Probes.....	41
Figure 8.	Temperature Measurement System.....	42
Figure 9.	Thermocouple Characteristics .....	42
Figure 10.	Traverse Used for Velocity Surveys.....	43
Figure 11.	Detail of Traversing Block Used for Velocity Surveys.....	44
Figure 12.	Traverse Used for Near Wall Profiles .....	45
Figure 13.	Detail of Traversing Block Used for Near Wall Profiles .....	46
Figure 14.	A Typical Hot-wire Calibration.....	47
Figure 15.	Inlet Turbulence Intensities .....	48
Figure 16.	Streamwise Mean Velocity Contours, $De=50.2$ to $De=125.4$ .....	49
Figure 17.	Streamwise Mean Velocity Contours, $De=125.4$ to $De=200.7$ .....	50
Figure 18.	Streamwise Mean Velocity Contours, $De=200.7$ to $De=275.9$ .....	51
Figure 19.	Streamwise Mean Velocity Contours, $De=301.0$ to $De=451.5$ .....	52
Figure 20.	Maximum and Minimum Streamwise Mean Velocities, $De=50.2$ to $De=451.5$ .....	53
Figure 21.	Maximum and Minimum Mean Velocities as Compared With Fields .....	54
Figure 22.	$\bar{u} - u_{CCPF}$ Contours, $De=50.2$ to $De=125.4$ .....	55

Figure 23.	$\bar{u} - u_{CCPF}$ Contours, De=125.4 to De=200.7 .....	56
Figure 24.	$\bar{u} - u_{CCPF}$ Contours, De=200.7 to De=275.9 .....	57
Figure 25.	$\bar{u} - u_{CCPF}$ Contours, De=301.0 to De=451.5 .....	58
Figure 26.	Streamwise Velocity Perturbation, $e$ , vs Dean Number .....	59
Figure 27.	Longitudinal Reynolds Normal Stress Normalized by the Local Mean Velocity Squared, De=50.2 to De=125.4.....	60
Figure 28.	Longitudinal Reynolds Normal Stress Normalized by the Local Mean Velocity Squared, De=125.4 to De=200.7 .....	61
Figure 29.	Longitudinal Reynolds Normal Stress Normalized by the Local Mean Velocity Squared, De=200.7 to De=275.9 .....	62
Figure 30.	Longitudinal Reynolds Normal Stress Normalized by the Local Mean Velocity Squared, De=301.0 to De=451.5 .....	63
Figure 31.	Longitudinal Reynolds Normal Stress Normalized by the Bulk Velocity Squared, De=50.2 to De=125.4.....	64
Figure 32.	Longitudinal Reynolds Normal Stress Normalized by the Bulk Velocity Squared, De=125.4 to De=200.7 .....	65
Figure 33.	Longitudinal Reynolds Normal Stress Normalized by the Bulk Velocity Squared, De=200.7 to De=275.9 .....	66
Figure 34.	Longitudinal Reynolds Normal Stress Normalized by the Bulk Velocity Squared, De=301.0 to De=451.5 .....	67
Figure 35.	Maximum and Minimum Longitudinal Reynolds Stress, De=50.2 to 451.5 .....	68
Figure 36.	Maximum Value of Longitudinal Reynolds Normal Stress Within Left Most Upwash Region .....	69



Figure 37.	Longitudinal Reynolds Normal Stress for $Y/d=0.1$ Within Left Most Upwash Region.....	70
Figure 38.	Longitudinal Reynolds Normal Stress for $Y/d=0.5$ Within Left Most Upwash Region.....	71
Figure 39.	Longitudinal Reynolds Normal Stress for $Z/d=5.2$ , $Y/d=0.1$ Within Left Most Upwash Region .....	72
Figure 40.	Longitudinal Reynolds Normal Stress Within Left Most Upwash Region, $De=50.2$ to $De=451.5$ . Data are presented for three positions: maximum value, $Y/d=0.1$ , and $Y/d=0.5$ .....	73
Figure 41.	Longitudinal Reynolds Normal Stress Within Left Most Upwash Region, $De=50.2$ to $De=275.9$ . Data are presented for three positions: maximum value, $Y/d=0.1$ , and $Y/d=0.5$ .....	74
Figure 42.	Longitudinal Reynolds Normal Stress Within Left Most Upwash Region, $De=50.2$ to $De=125.4$ . Data are presented for three positions: maximum value, $Y/d=0.1$ , and $Y/d=0.5$ .....	75
Figure 43.	Streamwise Mean Velocity Profiles, $De=125$ .....	76
Figure 44.	Mean Velocity Profiles in Wall Coordinates, $De=125$ .....	77
Figure 45.	Streamwise Mean Velocity Profiles, $De=170$ .....	78
Figure 46.	Streamwise Mean Velocity Profiles, $De=240$ .....	79
Figure 47.	Streamwise Mean Velocity Profile, $De=401$ .....	80
Figure 48.	Mean Velocity Profile in Wall Coordinates, $De=401$ .....	81
Figure 49.	Semi-log Plot of Streamwise Mean Velocity Profile in Wall Coordinates, $De=401$ .....	82
Figure 50.	Longitudinal Reynolds Normal Stress Profiles, $De=125$ .....	83
Figure 51.	Longitudinal Reynolds Normal Stress Profiles, $De=170$ .....	84

Figure 52.	Longitudinal Reynolds Normal Stress Profiles, $De=240$ .....	85
Figure 53.	Longitudinal Reynolds Normal Stress Profiles, $De=401$ .....	86
Figure 54.	Normalized Longitudinal Reynolds Stress Profiles, $De=125$ .....	87
Figure 55.	Normalized Longitudinal Reynolds Stress Profiles, $De=170$ .....	88
Figure 56.	Normalized Longitudinal Reynolds Stress Profiles, $De=240$ .....	89
Figure 57.	Normalized Longitudinal Reynolds Stress Profiles, $De=401$ .....	90
Figure 58.	Normalized RMS Intensity, $De=125$ .....	91
Figure 59.	Normalized RMS Intensity, $De=170$ .....	92
Figure 60.	Normalized RMS Intensity, $De=240$ .....	93
Figure 61.	Normalized RMS Intensity, $De=401$ .....	94
Figure 62.	RMS Intensity Normalized by Friction Velocity, $De=401$ .....	95
Figure 63.	RMS Intensity Normalized by the Maximum Velocity, $De=401$ .....	96
Figure 64.	Streamwise Mean Velocity Contour, $De=50.2$ .....	97
Figure 65.	Streamwise Mean Velocity Contour, $De=60.2$ .....	98
Figure 66.	Streamwise Mean Velocity Contour, $De=70.2$ .....	99
Figure 67.	Streamwise Mean Velocity Contour, $De=80.3$ .....	100
Figure 68.	Streamwise Mean Velocity Contour, $De=90.4$ .....	101
Figure 69.	Streamwise Mean Velocity Contour, $De=100.4$ .....	102
Figure 70.	Streamwise Mean Velocity Contour, $De=125.4$ .....	103
Figure 71.	Streamwise Mean Velocity Contour, $De=150.6$ .....	104
Figure 72.	Streamwise Mean Velocity Contour, $De=160.5$ .....	105
Figure 73.	Streamwise Mean Velocity Contour, $De=170.6$ .....	106
Figure 74.	Streamwise Mean Velocity Contour, $De=180.7$ .....	107
Figure 75.	Streamwise Mean Velocity Contour, $De=190.7$ .....	108
Figure 76.	Streamwise Mean Velocity Contour, $De=200.7$ .....	109

Figure 77.	Streamwise Mean Velocity Contour, $De=225.7$ .....	110
Figure 78.	Streamwise Mean Velocity Contour, $De=230.8$ .....	111
Figure 79.	Streamwise Mean Velocity Contour, $De=240.8$ .....	112
Figure 80.	Streamwise Mean Velocity Contour, $De=250.8$ .....	113
Figure 81.	Streamwise Mean Velocity Contour, $De=263.3$ .....	114
Figure 82.	Streamwise Mean Velocity Contour, $De=275.9$ .....	115
Figure 83.	Streamwise Mean Velocity Contour, $De=301.0$ .....	116
Figure 84.	Streamwise Mean Velocity Contour, $De=326.1$ .....	117
Figure 85.	Streamwise Mean Velocity Contour, $De=351.1$ .....	118
Figure 86.	Streamwise Mean Velocity Contour, $De=376.2$ .....	119
Figure 87.	Streamwise Mean Velocity Contour, $De=401.3$ .....	120
Figure 88.	Streamwise Mean Velocity Contour, $De=426.4$ .....	121
Figure 89.	Streamwise Mean Velocity Contour, $De=451.5$ .....	122
Figure 90.	Longitudinal Reynolds Normal Stress Contour, $De=50.2$ .....	123
Figure 91.	Longitudinal Reynolds Normal Stress Contour, $De=60.2$ .....	124
Figure 92.	Longitudinal Reynolds Normal Stress Contour, $De=70.2$ .....	125
Figure 93.	Longitudinal Reynolds Normal Stress Contour, $De=80.3$ .....	126
Figure 94.	Longitudinal Reynolds Normal Stress Contour, $De=90.4$ .....	127
Figure 95.	Longitudinal Reynolds Normal Stress Contour, $De=100.4$ .....	128
Figure 96.	Longitudinal Reynolds Normal Stress Contour, $De=125.4$ .....	129
Figure 97.	Longitudinal Reynolds Normal Stress Contour, $De=150.6$ .....	130
Figure 98.	Longitudinal Reynolds Normal Stress Contour, $De=160.5$ .....	131
Figure 99.	Longitudinal Reynolds Normal Stress Contour, $De=170.6$ .....	132
Figure 100.	Longitudinal Reynolds Normal Stress Contour, $De=180.7$ .....	133
Figure 101.	Longitudinal Reynolds Normal Stress Contour, $De=190.7$ .....	134

Figure 102. Longitudinal Reynolds Normal Stress Contour, $De=200.7$ .....	135
Figure 103. Longitudinal Reynolds Normal Stress Contour, $De=225.7$ . ....	136
Figure 104. Longitudinal Reynolds Normal Stress Contour, $De=230.8$ .....	137
Figure 105. Longitudinal Reynolds Normal Stress Contour, $De=240.8$ .....	138
Figure 106. Longitudinal Reynolds Normal Stress Contour, $De=250.8$ .....	139
Figure 107. Longitudinal Reynolds Normal Stress Contour, $De=263.3$ .....	140
Figure 108. Longitudinal Reynolds Normal Stress Contour, $De=275.9$ .....	141
Figure 109. Longitudinal Reynolds Normal Stress Contour, $De=301.1$ .....	142
Figure 110. Longitudinal Reynolds Normal Stress Contour, $De=326.1$ .....	143
Figure 111. Longitudinal Reynolds Normal Stress Contour, $De=351.1$ .....	144
Figure 112. Longitudinal Reynolds Normal Stress Contour, $De=376.2$ .....	145
Figure 113. Longitudinal Reynolds Normal Stress Contour, $De=401.3$ .....	146
Figure 114. Longitudinal Reynolds Normal Stress Contour, $De=426.4$ .....	147
Figure 115. Longitudinal Reynolds Normal Stress Contour, $De=451.5$ .....	148
Figure 116. Streamwise Mean Velocity Contour (prior to channel cleaning), $De=125.4$ .....	149
Figure 117. Streamwise Mean Velocity Contour (prior to channel cleaning), $De=175.6$ .....	150
Figure 118. Longitudinal Reynolds Normal Stress Contour (prior to channel cleaning), $De=125.4$ .....	151
Figure 119. Longitudinal Reynolds Normal Stress Contour (prior to channel cleaning), $De=175.6$ .....	152

## NOMENCLATURE

$C$	Temperature Correction Function
CCPF	Curved Channel Poiseuille Flow
$d$	Channel Height, $(r_o - r_i)$
$De$	Dean Number, $(Re_d)\sqrt{d/r_i}$
$e$	Streamwise Velocity Perturbation
$E, E_{meas}$	Mean Output Voltage from Anemometer Bridge
$E_{corr}$	Temperature Corrected Bridge Output Voltage
$E_{oc}$	Zero Velocity Intercept of Best-Line Fit of Calibration Data
$OHR$	Overheat Ratio
$R_c$	Hot-Wire Cold Resistance
$Re_d$	Reynolds Number Based on Channel Height
$Re_\tau$	Reynolds Number Based on Friction Velocity and Channel Half-Height
$R_H$	Hot-Wire Hot Resistance
$r_i$	Curved Channel Inside Radius
$r_o$	Curved Channel Outside Radius
$T_{cal}$	Freestream Temperature at Time of Calibration
$T_\infty$	Freestream Temperature at Commencement of Surveys
$T_{meas}$	Freestream Temperature as it Varies with Time
$U_{bulk}$	Bulk Mean Velocity Used to Determine $De$
$u_{CCPF}$	Streamwise Velocity Assuming CCPF
$\bar{u}$	Streamwise Mean Velocity
$U$	Instantaneous Velocity, $\bar{u} + u'$

$u_\tau$	Friction Velocity
$u^+$	Wall Coordinate for Streamwise Mean Velocity, $u / u_\tau$
$\overline{u'^2}$	Longitudinal Reynolds Normal Stress
$X/d$	Normalized Streamwise Direction
$y^+$	Wall Coordinate in Radial Direction, $Y u_\tau / \nu$
$Y/d$	Normalized Radial Direction
$Z/d$	Normalized Spanwise Direction

### Greek Symbols

$\alpha$	Temperature Coefficient of Resistance for Hot-Wire Probe
$\delta$	Channel Half-Height, $d/2$
$\rho$	Density
$\nu$	Kinematic Viscosity
$\theta$	Streamwise Location from Start of Curvature
$\tau_w$	Shear Stress at the Wall

## ACKNOWLEDGMENT

I would like to express my appreciation to those who made this work possible. Particularly, Professor Ligrani who provided inspiration and guidance from the very beginning and Professor Subramanian who never hesitated in coming to my aid, providing the technical know-how needed to get me through. Most of all, I would like to thank my family, Kathi, Steven and Matthew, without whose support and encouragement none of this would have been possible. Thank you.

## I. INTRODUCTION

Curved channels with rectangular cross-sections are important in regard to a number of components of interest to the U.S. Navy. Such channels exist within heat exchangers used in applications ranging from gas turbine engines to steam power plants. Curved cooling passages with rectangular cross-sections are also present within interior portions of gas turbine blades. Results from the curved channel study are also applicable to situations in which unbounded flows move over concave surface curvature (i.e., concave sides of gas turbine blades and airfoils) because the physical phenomena in the two situations are very similar. The present work is important for these applications first, because it provides information to designers constructing such facilities, secondly, because it provides basic information needed by researchers who are developing prediction schemes for these channels, and thirdly, because it provides new physical insight into the behavior of fluid dynamics and heat transfer phenomena in these practical applications.

### A. BACKGROUND

Flow in a curved rectangular channel is characterized by the Dean number, defined as the Reynolds number based on channel height  $d$  and bulk streamwise velocity times a curvature factor equal to  $(d/r_i)^{1/2}$ , where  $r_i$  is the radius of the convex surface.

$$De = Re_d \sqrt{\frac{d}{r_i}} \quad \{1.1\}$$

At a given streamwise location, flow is two-dimensional and laminar at low Dean numbers. This is curved channel Poiseuille flow. Dean [Ref. 1], using analytical means, first demonstrated that curved channel flow is unstable to small amplitude disturbances for  $De > 36$ . Above this critical Dean number, pairs of counter-rotating vortices develop in



the laminar flow as the primary instability. Brewster *et al.* [Ref. 2] experimentally found pairs of steady counter-rotating vortices for conditions when the channel is unstable to small amplitude disturbances, providing experimental verification of the theoretical work by Dean. Numerical work by Finlay [Ref. 3] predicts these vortices become unstable at higher  $De$  to two types of travelling waves, resulting in two kinds of wavy vortex flows, referred to as undulating Dean vortex flow and twisting Dean vortex flow. The first photographic evidence of vortex motions believed to be twisting is presented by Ligrani and Niver [Ref. 4]. However, the first mention of experimentally observed waviness is given by Kelleher *et al.* [Ref. 5]. Additional evidence of wavy vortex flow is given by Matsson and Alfredsson for a curved channel, with and without rotation [Refs. 6, 7]. Ligrani *et al.* [Ref. 8] present additional experimental evidence of wavy vortex motions associated with undulating and twisting and compare these results with numerical predictions. Numerical simulations by Moser and Moin [Ref. 9] predict the behavior of longitudinal turbulence intensity in a curved channel with fully turbulent flow. A recent work by Bottaro *et al.* [Ref. 10] considers the spatial development of the flow in a curved channel from experimental measurements and using three-dimensional finite-volume simulations.

The present study continues efforts by Niver [Ref. 11], Baun [Ref. 12], Longest [Ref. 13], Fields [Ref. 14] and Kendall [Ref. 15] on the same curved channel. Niver's flow visualization results provided the first photographic evidence of twisting and undulating vortex flow. Baun continued this work by studying the time-averaged flow field and power spectra for Dean numbers from 50 to 250. Longest's flow visualization results provided photographic evidence of vortex pair merging and splitting at Dean numbers of 75 and 100. Fields conducted a comprehensive study in a cleaner, or less disturbed flow, for Dean numbers from 35 to 425 that showed evidence of vortex pairs to a

higher Dean number than previously observed by Baun. Kendall conducted a detailed analysis of merging and splitting phenomena for Dean numbers from 60 to 150. Kendall also focussed on unsteady Dean vortex pair behavior as evidenced by spectra and correlation measurements.

The present study is motivated by the fact that little is known about the character of longitudinal turbulence intensity in laminar and transitioning curved channel flows. Of particular interest is the relationship between twisting and local increases of the longitudinal Reynolds normal stress.

## **B. OBJECTIVES**

The primary objective of this study is to investigate the variations in the longitudinal turbulence intensity as they occur at different locations in the channel over a range of Dean numbers. These data are intended to give insight into transition to a fully turbulent flow from a laminar flow containing a spanwise array of vortex pairs. Particular attention is devoted to twisting and its relation to local increases of longitudinal normal Reynolds stress.

## **C. ORGANIZATION**

The material in this thesis is organized as follows. Chapter II describes the curved channel and equipment used for measurement of surveys and near wall profiles. Chapter III describes the experimental procedures used. Experimental results are presented in Chapter IV. Summary and conclusions are presented in Chapter V. Figures are presented in Appendix A and Appendix B presents a software directory of the programs used. Appendix C provides a directory of the data files generated in support of this work.

## II. EXPERIMENTAL APPARATUS

The apparatus used in this study are located in the laboratories of the Mechanical Engineering Department of the Naval Postgraduate School. They primarily consist of a transparent curved channel, a data acquisition system and a traversing mechanism.

### A. CURVED CHANNEL

The curved channel is described in detail by Ligrani and Niver [Ref. 4]. A schematic illustration and photograph of the facility are shown in Figures 1 and 2, respectively. A brief discussion of the facility follows.

#### 1. Description of the Facility

The channel is an open-circuit suction facility developed to study transitional flows. At the inlet, an aluminum honeycomb and three screens reduce spatial non-uniformities in the flow. These are followed by a *two-dimensional nozzle* with a 20 to 1 contraction ratio that accelerates the flow into a 2.44 meter long straight duct [Ref. 8]. The duct is followed by a curved test section shown schematically in Figure 3. The 180 degree curved section is followed by another 2.44 meter long straight duct, a honeycomb, several screens, a diffuser, then an outlet plenum. The outlet plenum is connected to a second plenum using 50.8 mm diameter tubing. This second plenum is maintained at a low pressure by a 1/3 horsepower blower manufactured by ICG Industries, Inc. The blower is connected to the second plenum using a flexible coupling to prevent motor vibrations from affecting the upstream flow. A globe valve between the plenums is used to adjust the flow rate.

The test probe is inserted into the flow through a slot in the convex wall of the test section at a streamwise location  $120^\circ$  from the start of curvature. The slot is 0.32 cm

wide, 7.62 cm long and is aligned in the spanwise direction 5.08 cm from the channel centerline. A support block (see Figures 4 and 5) made of polycarbonate (15.24 cm by 6.35 cm by 2.22 cm) is joined using epoxy to the wall surrounding the slot to maintain the wall's dimensional integrity and to minimize the deflection of the curved wall in the vicinity of the slot. Foam is used to line the slot to allow probe insertion with no air leakage into the test section [Ref. 8]. This arrangement allows the probe to be positioned at different locations within a spanwise/radial plane.

## **2. Cleaning the Channel**

The small scale disturbances leading to transition are believed to be initiated at the nozzle inlet or in the boundary layers developing along the nozzle. Dust buildup on the walls of the flow management unit and on the walls of the channel itself are thus a concern because these may create disturbances which affect transition behavior. According to Saric [Ref. 16], wall discontinuities with heights of 0.3-0.6 microns can have severe effects on transition development in a channel. To minimize this problem, the channel and inlet section were cleaned using a commercial glass cleaner with ammonia (Windex) and a lint free cloth. Changes to the flow resulting from this cleaning are described in Section IV D.

## **B. PROBES, ELECTRONICS AND DATA ACQUISITION SYSTEM**

The present study employs hot-wire anemometry for the measurement of turbulence and unsteady laminar flows. Perry [Ref. 17] describes principles of hot-wire anemometer operation. According to him, an electric current is passed through a fine filament that is exposed to a cross flow. As the flow rate varies, the heat transfer from the filament varies. This, in turn, causes a variation in the heat balance of the filament. There are two modes of operation of a hot-wire system, constant current and constant temperature. The constant temperature mode is used in this study. Here, the filament is placed in a feedback circuit that tends to maintain the wire at a constant resistance, and hence, constant temperature.

Fluctuations in the cooling of the filament are then seen as variations in wire current. The current is sensed by placing the filament in a resistance bridge so that variations in current result in changes in the bridge output voltage. Using appropriate calibration relationships, this voltage is related to the flow velocity.

The data acquisition system and probe traverse are shown schematically in Figure 6. Specific components are described in detail in the following section.

### **1. Hot-wire Probes**

DANTEC type 55P14 and DANTEC type 55P04 probes are used in these experiments. These probes are shown in Figure 7 [Ref. 18]. The sensors of these probes are 90% platinum - 10% rhodium wire with a 5  $\mu\text{m}$  diameter. The active length of each wire is 1.25 mm. The overall length of the sensors and plated end wires of type 55P14 probes is 1.25 mm and the overall wire length of type 55P04 probes is 3 mm. The cold resistance of each wire is about 4 - 5 ohms and an overheat ratio of 1.8 is used in all experiments. The temperature coefficient of resistance,  $\alpha$ , is 0.0036 ohms/ $^{\circ}\text{C}$ . Each probe is mounted using a DANTEC type 55H21 probe support, and is positioned in the channel as shown in Figure 4.

### **2. Hot-wire Anemometer Bridge**

A DANTEC model 55M10 constant temperature bridge is used to operate the hot-wires with a HF FILTER setting of 2 and GAIN ADJUST setting of 4. The hot-wire is connected to the bridge using a 5 meter long BNC cable. Dynamic response is verified using the .3 kHz square wave generator within the bridge. Typically, the "-3 dB" point (frequency at which mean square response has fallen to half its nominal value) is about 125 kHz. Actual system response is less, however, because frequency response is most often limited by the spatial resolution of the probe [Ref. 19]. The anemometer has two BNC cable connectors for analog signal output. One output is connected as an input to the

signal conditioner and the second output is connected directly to an oscilloscope to provide a visual indication of the voltage signal from the hot-wire bridge.

### **3. Signal Conditioner**

A DANTEC model 56N20 signal conditioner is used to amplify and low pass the bridge output prior to analog-to-digital (A/D) conversion. A gain of 2 (with 0 offset voltage) is used to provide a dynamic signal within the  $\pm 10$  V range of the analog-to-digital converter. The high pass filter is set to DC, and the low pass filter is set to 1 kHz for Dean numbers up to 275 and to 3 kHz for Dean numbers beyond 275. The LP filter was used to remove spurious electronic noise from the bridge output and to prevent aliasing. To minimize attenuation of the data signal, the low pass filter setting was changed at Dean number of 275 based on power spectra for similar flow conditions from Fields [Ref. 14]. At the higher Dean numbers, the turbulence energy levels are insignificant at frequencies beyond 3 kHz.

### **4. Analog-to-Digital Converter**

The analog signal from the signal conditioner is digitized using a Hewlett-Packard 6944A Series 200 Multiprogrammer with a buffered 69759A A/D card capable of 12-bit binary resolution. As configured, the multiprogrammer can support two channels, however only one channel is used for this study. Sample size and sampling frequency for each data point are specified so that accurate time-averaged magnitudes of flow properties are obtained. Throughout this experiment, a total of 20,000 samples are acquisitioned at each data point. At low Dean numbers (less than 275), a total sampling frequency of 5,000 Hz is used for two channels (2,500 Hz per channel), resulting in a total of 8 seconds of sampled data at each measurement point. For higher Dean numbers (275 and above), a total sampling frequency of 5,000 Hz per channel is used, resulting in 4 seconds of data at each measurement point.

The gain and offset of the data acquisition system are measured using procedures described by Green [Ref. 20]. The offset for the channel employed is found by shorting the signal conditioner input and then recording the output from the analog-to-digital converter. The system gain for a particular channel is found by inputting a 1.5 kHz sinusoidal signal of known RMS voltage and comparing this value to the RMS voltage at the output of the analog-to-digital converter. Typical values for gain and offset are 1.918 and -0.006, respectively.

### **5. Microcomputer**

A HP series 9000 Model 310 computer is used to collect and process data from the A/D converter. With the available memory, the computer is capable of storing and processing only about 5000 samples of data. To obtain 20,000 samples for each measured point, the data acquisition software collects data in batches of 5000, processes them, stores intermediate results, and then repeats this process four times. The HP series 9000 Model 310 computer is also used to control the probe traversing equipment. Data processing is done using the software HOTWIREu described in Appendix B.

### **6. Temperature Measurement**

The temperature of the flow entering the curved channel is measured using a T-type copper-constantan thermocouple connected to a low-speed data acquisition system, which is shown schematically in Figure 8. This system is entirely independent from the high-speed system mentioned above. The calibration characteristics of the thermocouple are shown in Figure 9. From this calibration, the relationship between voltage and temperature is approximated using a third-order polynomial given by:

$$T(^{\circ}\text{C}) = 9.5767 - 1.0241e+4 E(V) + 4.5290e+7 E(V)^2 - 1.9205e+10 E(V)^3 \quad \{2.1\}$$

Temperatures are measured at 10 minute intervals during most of the experiments using the program TEMPMEAS run on a second HP series 9000 Model 310 computer.

## **C. PROBE TRAVERSING DEVICES**

### **1. Survey Apparatus**

Surveys of streamwise mean velocity and longitudinal Reynolds stress are made over a 0.35 inch by 2.0 inch spanwise/radial plane normal to the streamwise direction. This plane is divided into 328 grid locations (8 radial by 41 spanwise) spaced 0.05 inch apart in both directions. During a survey, the probe is positioned at each of these positions using an automated two-dimensional traversing mechanism shown in Figures 10 and 11. Within this mechanism, the probe is attached to a mount which is secured to a travelling block that is moved in the radial and spanwise directions by two lead screws, each with 20 threads-per-inch pitch. The lead screws are rotated using D.C. stepping motors (SLO-SYN M092-FD310) that are controlled by a MODULYNX MITAS type PMS085-C2AR controller and driven by a MODULYNX MITAS type PMS085-D050 drive [Ref. 20]. The controller is linked to the microcomputer through a built-in RS-232 interface. The motor controller is operated in the remote mode, which allows probe traversing commands to be executed from the data acquisition software program HOTWIREu.

### **2. Near Wall Apparatus**

Near wall profiles are obtained using the same data acquisition system mentioned above, and a slightly modified version of the same traverse. The 20 thread-per-inch rod for the radial component of motion is replaced with one with 100 threads-per-inch pitch. The hardware components are shown in Figures 12 and 13. Additionally, the travelling block used to mount the probe is constructed as to minimize the effect of backlash, and software is altered to account for the new threaded rod. With these modifications, the resolution of the radial position is increased by a factor of 5.



The near-wall profiles are difficult to obtain due to the proximity of probes to the channel wall and the fragile nature of the hot-wire probes. The sensors of the probes employed for this part of the study were constructed in-house. To accomplish this, DANTEC 55P04 probe mounts were employed, to which silver-plated platinum (90%)-rhodium (10%) wire was soldered. The silver coating was then etched to expose a 1.25 mm active length using a 40% nitric acid solution in distilled water. During the etching process, a current of about 100 mA was passed through the sensing wire.

### III. EXPERIMENTAL PROCEDURES

#### A. HOT-WIRE CALIBRATION

The hot-wire probes are calibrated in an open circuit subsonic wind tunnel using procedures for low velocity measurement described by Ligrani and Bradshaw [Ref. 19]. The velocity calibration is performed by placing hot-wire probes in the flow with individual wires oriented normal to the flow. The mean velocity,  $U$ , is varied from 1 to 10 m/s and the corresponding bridge output voltage is then recorded.

Typical results are shown in Figure 14. Here the data is shown with  $E^2 - E_{oc}^2$  plotted against  $U^{0.45}$ , where  $E$  is the mean voltage and  $E_{oc}$  is the zero velocity intercept of the best-fit line (not the actual zero-flow voltage). At moderate velocities, the relationship is linear and may be approximated by:

$$U^{0.45} = \frac{1}{B} (E^2 - E_{oc}^2) \quad \{3.1\}$$

where  $B$  is a calibration constant.

At lower velocities, the calibration data is assumed to be non-linear. Ligrani and Bradshaw [Ref. 19] have found that hot-wires of this type exhibit linear behavior for  $Re_d \geq 0.07$ , where  $Re_d$  is the Reynolds number based on wire diameter. For velocities below this limit, they propose a third-order polynomial relationship of the form:

$$\alpha = a_0 + a_1\beta + a_2\beta^2 + a_3\beta^3 \quad \{3.2\}$$

where  $\alpha = U^{0.45}$ ,  $\beta = E^2 - E_{oc}^2$  and  $a_0$ ,  $a_1$ ,  $a_2$  and  $a_3$  are calibration constants. The calibration constants are determined so that equations {3.1} and {3.2} form a continuous

function as  $\alpha$  varies. When data are processed, only equation {3.1} is employed in the form of a look-up table as the lowest  $Re_d$  encountered was greater than 0.07.

Before each calibration, the electronics are allowed to warm up to steady-state condition. The cold resistance is obtained with flow past the probe, then an overheat ratio of 1.8 is applied. During calibration, the HF FILTER and GAIN ADJUST of the DANTEC 55M01 bridge are adjusted to optimize frequency response of the probe. A HF FILTER setting of 2 and GAIN ADJUST of 4 were determined to be the best choice for optimal response.

## **B. DEAN NUMBER DETERMINATION**

The flow rate or Dean number is set by referring to the pressure drop across a standard 1.5 inch ASME orifice plate. The details of this procedure are presented by Fields [Ref. 14]. For all runs prior to run number 070391.2145<sup>1</sup>, the pressure drop was measured with a 0 - 0.5 inch range Meriam model 40GD10WM inclined tube manometer or a 0 - 4 inch range Meriam model 40HE35WM inclined tube manometer. For run number 070391.2145, and all runs thereafter, the pressure drop was measured with a 0 - 2 inch Validyn model PS309 digital manometer. The digital manometer is preferred because it yields good accuracy over all Dean numbers of interest.

## **C. MEASUREMENT OF DEAN NUMBER SURVEYS**

### **1. Procedures**

Details of the measurement procedures used to obtain the surveys are now discussed. At the beginning of these procedures, the DANTEC probe holder is placed into

---

<sup>1</sup>Run numbers are specified in a MMDDYY.hhmm format, where MM, DD, and YY indicate the month, day and year of the run and hh and mm indicate the hour and minute of the run. This convention is used throughout this study.

the probe mounting block which is attached to a travelling block on the traverse. The travelling block is then located as close to the curved channel as possible. This probe holder is visually aligned with the slot with the foam removed. Foam is ordinarily located in the slot located in the convex wall to prevent air leakage around the probe as it traversed through the spanwise/radial plane. The hot-wire probe is then inserted into the holder and then carefully guided through the slot and positioned so that the probe is located at a radial location of  $Y/d = 0.1$ . Continuity of the wire is subsequently verified using the DANTEC bridge. Afterwards, the foam is replaced into the convex wall slot.

With the probe now in the flow, the cold resistance,  $R_c$ , is measured using the DANTEC bridge. The hot resistance,  $R_H$ , may then be calculated using an equation of the form:

$$R_H = R_c \times OHR \quad \{3.3\}$$

where  $OHR$  is the overheat ratio. This operating resistance is set on the bridge and the bridge is placed in the "operate" mode.

Data collection begins with the probe 0.05 inches from the concave wall ( $Y/d = 0.1$ ) at the first spanwise position which is at  $Z/d = 4.0$  or  $2.0$  inches from the spanwise centerline of the channel. As the survey continues, the probe moves towards the convex wall in 0.05 inch steps. Eight radial steps are made at each spanwise location. To move to the next spanwise position the probe is moved 0.1 inch in the negative spanwise direction, then 0.05 inch in the reverse (or positive) spanwise direction, and then it is repositioned radially to a location 0.05 inches from the concave surface. This positioning procedure is used to reduce the effects of leadscrew backlash and ensure repeatable data regardless of the direction of spanwise probe movements [Ref. 4].

At each probe position within the channel, 20,000 samples are taken. Afterwards, the data are processed and the probe is moved to the next station. After the probe is moved to each new station, measurements are delayed 10 seconds to allow any unsteadiness introduced into the flow by the probe movements to dissipate. Approximately 8 hours are required to complete a survey of 328 points. During the survey, the temperature of the air entering the channel is recorded so that corrections can be made later to account for ambient temperature variations.

## 2. Data Reduction

### a. Calculation of Turbulence Statistics

As previously mentioned, the collection of 20,000 samples at each node is done in 4 loops, each containing 5000 samples. Turbulence statistics are calculated and averaged for each loop; the averages from the four loops are then averaged. The turbulence statistics are calculated as follows:

$$\bar{u} = S_u$$

$$\overline{u'^2} = S_{uu} - S_u S_u \quad \{3.4\}$$

where:

$$S_u = \frac{1}{20,000} \sum_{loop=1}^4 \sum_{sample=1}^{5,000} U$$

$$S_{uu} = \frac{1}{20,000} \sum_{loop=1}^4 \sum_{sample=1}^{5,000} UU \quad \{3.5\}$$

In these equations,  $U$  is the instantaneous velocity ( $U = \bar{u} + u'$ ).

### ***b. Temperature Drift Correction***

According to Perry [Ref. 17], one of the most important sources of error in hot-wire measurements is the failure to account correctly for mean ambient temperature variations. Ideally, measurements should be taken at the same temperature as the calibration (i.e., if variations are within  $\pm 1/2^\circ\text{C}$  throughout calibration and measurement procedures, corrections are unnecessary).

The velocity surveys were performed days, sometimes weeks, following calibration and the surveys themselves require about 8 hours to complete. Because the laboratory facility does not have an effective temperature control system a temperature correction was thus necessary. Green [Ref. 20] recommends a correction be applied to this measured bridge voltage,  $E_{meas}$ , which is given by:

$$E_{corr} = E_{meas}(1 + C) \quad \{3.6\}$$

where  $E_{corr}$  = corrected voltage and  $C$  = Temperature correction function given by:

$$C = \frac{\alpha}{2(OHR - 1)} (T_\infty - T_{cal}) \quad \{3.7\}$$

where  $\alpha$  = temperature coefficient of resistance,  $OHR$  = overheat ration,  $T_\infty$  = freestream temperature and  $T_{cal}$  = freestream temperature at time of calibration.

The correction given by equation {3.6} and {3.7} is applied to the look-up table which is constructed for data reduction using equations {3.1} and {3.2} at the start of each survey [Ref. 20]. Applying the temperature correction in this manner accounts for the differences in temperature between  $T_\infty$  measured at the start of a survey and  $T_{cal}$ . Because of variations in  $T_\infty$  during a survey, a second correction was sometimes necessary. This correction was applied to the data by first determining the corrected voltage from the mean velocity  $\bar{u}$  using the equation given by:

$$E_{corr}^2 = E_{oc}^2 + B \bar{u}^{0.45} \quad \{3.8\}$$

This voltage was then corrected for variations between  $T_\infty$  and  $T_{meas}$  using:

$$E_{corr}^* = E_{corr} (1 + C^*) \quad \{3.9\}$$

where  $T_{meas}$  is the freestream temperature as it varies with time, and where:

$$C^* = \frac{\alpha}{2(OHR - 1)} (T_{meas} - T_\infty) \quad \{3.10\}$$

Velocities corrected to account for temperature drift during a run may then be calculated using the equation given by:

$$\bar{u}^{0.45} = \frac{1}{B} (E_{corr}^{*2} - E_{oc}^2) \quad \{3.11\}$$

Temperature drift was most apparent in the surveys of streamwise mean velocity. The measured quantity  $\bar{u}^2$  did not show significant evidence of temperature drift during a survey, and therefore, this correction was not applied to measurements of  $\bar{u}^2$ .

#### D. PROCEDURES FOR MEASUREMENT OF NEAR WALL PROFILES

Near wall profiles are obtained using procedures similar to those used in obtaining surveys with several exceptions. First, the probe is initially placed at a radial position 0.015 inches from the concave wall. This is done in the following manner. First, an expendable, or *dummy*, probe (with no usable sensor) is placed in the channel in contact with the concave wall. This establishes a reference, or zero, position. Using the MITAS controller, this *dummy* probe is then positioned at the channel centerline. The *dummy* probe is then replaced with a calibrated probe using procedures previously discussed. Using the zero reference, the new probe is carefully positioned to the 0.015 inch position while monitoring bridge output voltage and probe response on the oscilloscope trace. To

account for any difference in the positions of the dummy probe and the actual measuring probe, additional correction was deemed necessary. This type of correction to the radial position is determined from data at a Dean number of 125 and is discussed in detail in the results.

During data acquisition, the probe is moved radially in steps of 0.005 inch for a total of 28 radial positions. Changes in spanwise position are done manually using the MITAS controller. When positioning in the spanwise direction, the probe is first moved to the channel centerline ( $Y/d = 0.5$ ) then positioned to the desired spanwise location, as a precaution against probe damage due to unevenness in the concave wall surface. The probe is then positioned at a radial location of 0.015 inches away from the concave wall. A new radial traverse then begins.

A complete near wall profile requires less than 40 minutes. During this short period of time, variations in ambient temperature were generally insignificant, and consequently no temperature drift corrections were necessary.



## IV. EXPERIMENTAL RESULTS

Streamwise mean velocity and longitudinal Reynolds normal stress as measured in a radial/spanwise plane located  $120^\circ$  from the start of curvature for Dean numbers from 50.2 to 451.5 are presented in this section. Each contour plot presented is obtained from a radial/spanwise plane survey of a grid 8 by 41 points spaced 0.05 inch apart in each direction. In these plots,  $Y$  and  $Z$  are normalized by the channel height,  $d$ , so that  $Y/d = 0.0$  represents the concave surface and  $Y/d = 1.0$  represents the convex surface.  $Z/d$  is measured with respect to the channel centerline.

Near wall profiles of streamwise mean velocity and longitudinal Reynolds normal stress are presented for three distinct spanwise locations for Dean numbers of 125, 170 and 240, and at one spanwise location for a Dean number of 401. Each profile plot was obtained from a radial survey of 28 grid locations spaced 0.005 inch apart.

Also presented in this chapter are results from turbulence intensity measurements taken at the exit of the channel nozzle.

### A. INLET TURBULENCE INTENSITY

The longitudinal turbulence intensity at the nozzle exit is measured using a DANTEC type 55P01 single-sensor hot-wire probe mounted normal to the flow direction and operated in constant temperature mode. The probe is located at  $X/d = 4.0$ ,  $Y/d = 0.5$  and  $Z/d = 5.75$ , where  $X/d$  is measured from the nozzle exit. The bridge output signal is high-pass filtered at 10 Hz and low-pass filtered at 1 kHz. These filter settings are chosen to obtain the turbulence intensity magnitudes representative of conditions at the inlet of the facility without contamination by low frequency laboratory disturbances and without contamination of any high frequency electronic noise.

Data obtained from these measurements are presented in Figure 15. Presented are values of longitudinal turbulence intensity normalized by the local mean velocity for Dean numbers of 223.5, 326.8 and 425.7. Also included in this figure are values obtained by Smith [Ref. 22] obtained from a straight channel with an inlet very similar to that used in this study (the only difference is that Smith's channel had cheese cloth over the inlet as an additional dust precipitator). Both facilities have the same nozzle design and dimensions, and same flow management apparatus consisting of three screens and a honeycomb. In the present study, the turbulence intensity varies from 0.0013 to 0.0015 compared values in the straight channel of 0.0011 to 0.0024. It should be noted the present data are contaminated by 60 Hz electronic noise, and therefore, the values presented in Figure 15 are higher than actual longitudinal turbulence intensities in the flow.

Removing all of the electronic noise from the signal is difficult because signal levels are so low. Ligrani and Niver [Ref. 4] give the turbulence intensities of the streamwise velocity at Dean numbers of 290 and 450 as 0.0006 and 0.0010, respectively. The results of Ligrani and Niver are believed to be more representative of the flow than ones measured presently because they used additional electronic filters to remove the 60 Hz electronic noise from the signal.

## **B. SURVEYS**

Surveys of time-averaged quantities are presented in Figures 16 through 42 and in Figures 64 through 119. Of these, contour plots of normalized streamwise mean velocity are presented in Figures 16 through 19. Velocity perturbation contours are presented in Figures 22 through 25. Normalized longitudinal Reynolds normal stress contours are presented in Figures 27 through 34. Figures 64 through 89 present individual contour plots of the dimensional streamwise mean velocity, and Figures 90 through 115 present individual contour plots of the dimensional longitudinal Reynolds normal stress. Figures

116 through 119 also present individual contour plots of the dimensional streamwise mean velocity and individual contour plots of the dimensional longitudinal Reynolds normal stress at  $De = 125$  and  $175$ , however these data were obtained prior to channel cleaning. All other survey data were obtained just after the channel was thoroughly cleaned.

### 1. Normalized Streamwise Mean Velocity

Normalized streamwise mean velocity surveys obtained with the single-sensor hot-wire probe are presented in Figures 16 through 19 for  $De = 50.2$  to  $451.5$ . These data are normalized by the bulk velocity,  $U_{bulk}$  (the same bulk velocity as that used to determine the Dean number).

At  $De = 50.2$ , Figure 16 shows that the flow is spanwise uniform, as expected. No local disturbances to the mean velocity are evident due to the presence of vortex pairs. However, there is evidence of vortex pairs in data for  $De = 60.2$  presented in the same figure. At this  $De$ , there are two significant velocity deficits within the survey: the first at  $Z/d = 6.0$  and the second at  $Z/d = 7.2$ . These deficits extend over approximately half the channel height from  $Y/d = 0.1$  to  $0.5$ . As the Dean number increases from  $70.2$  to  $150.6$ , the velocity deficits span the entire channel height. The presence of these deficits span the entire flow and appear to be *spanwise periodic*. Each deficit indicates the location of an *upwash* region between the two vortices (with respect to the concave wall) within each vortex pair. The time-averaged flow field also shows a vortex pair merging between  $De = 100.4$  and  $125.4$ . This is evident when the two deficits at  $Z/d = 7.5$  and  $8.0$  merge into one deficit at  $Z/d = 7.9$ . A similar occurrence is observed from  $De = 190.7$  to  $200.7$ .

Compared to results for  $De$  from  $70.2$  to  $150.6$ , the character of deficit regions changes as the Dean number varies from  $160.5$  to  $250.8$ . They become smaller in the radial direction and extend over larger spanwise distances. At  $De = 263.3$  through  $451.5$  the flow is more or less *spanwise uniform*, indicated by almost no evidence of vortex pairs

in the time averaged flow field. Vortex pairs may be present at these Dean numbers, however, if they are there, they are not apparent in time-averaged measurements because of considerable vortex pair unsteadiness in the spanwise and radial directions.

Some important features of these surveys are summarized in Figures 20 and 21. Figure 20 presents the minimum and maximum mean velocity measured in each survey grid. The maximum value is the actual maximum for the  $120^\circ$  spanwise/radial plane at each Dean number whereas the minimum value is only the minimum within  $Y/d = 0.1$  to  $0.8$ . The minimum and maximum bracket the bulk velocity, as expected. At Dean numbers from about 60.2 to 250.8, the location of the minimum velocity is in the upwash regions where velocity deficits are present.

Figure 21 presents the same data as Figure 20 compared with similar results obtained by Fields [Ref. 14]. Fields data was obtained using a miniature five-hole pressure probe and is presented here to show that agreement between the two sets of results is reasonably good. Contour plots are also in excellent agreement with those obtained by Fields, particularly, in regard to the detailed characteristics of individual velocity deficits. There are differences, however, in the spanwise position of vortex pairs between the present study surveys and ones from Fields. This is believed to be due to inlet channel disturbances caused by dirt accumulating on the walls and inlet flow management sections of the channel. This effect is discussed in greater detail later in this chapter.

## **2. Velocity Perturbation**

At small values of Dean number, the fluid motion in the curved channel is two-dimensional and laminar, without secondary flows. The velocity profile is nearly parabolic with the maximum shifted slightly toward the concave surface compared to flow in a straight channel. This velocity profile then corresponds to *curved channel Poiseuille flow* (CCPF) [Refs. 23, 24]. When the primary flow instability sets in at higher  $De$ , the velocity

profile is altered from the CCPF profile. To show deviations from curved channel Poiseuille flow, values of velocity corresponding to CCPF are subtracted from the streamwise mean velocity. The resulting velocity perturbation  $(\bar{u} - u_{CCPF})$  contours are presented in Figures 22 through 25 to illustrate perturbations to curved channel Poiseuille flow caused by time-averaged secondary flows.

In Figure 22 at  $De = 50.2$ , there are no observable variations in the mean velocities from CCPF. At  $De = 60.2$ , differences from CCPF become apparent. In particular, there are two circular shaped deficits at  $Z/d = 6.0$  and  $7.5$  that correspond to upwash regions (these also correspond to deficits in the streamwise mean velocity). As the Dean number increases from  $70.2$  to  $150.6$ , the deficits take the shape of upside down triangles. As the Dean number increases further from  $170.6$  to  $250.8$ , the deficit regions continue to change shape until the flow finally becomes spanwise uniform for Dean numbers from  $263.3$  to  $451.5$ . Results for  $De = 263.3$  to  $451.5$  from Figures 24 and 25, show significant deviations in the mean velocity from CCPF. This is because the flow is approaching a more turbulent flow profile.

From results like the ones presented in Figures 22 through 25, magnitudes of  $e$ , the streamwise velocity perturbation across the spanwise/radial measurement plane can be determined. This quantity  $e$  is given by:

$$e = \sqrt{\frac{1}{A} \int_A (u - u_{CCPF})^2 dA} \quad \{4.1\}$$

where  $A$  is the area of the cross-section and  $u_{CCPF}$  is the velocity assuming curved channel Poiseuille flow. This quantity represents the cumulative effect of variations of the streamwise mean velocity from CCPF due to the primary instability in the channel for a particular Dean number. Magnitudes of  $e$  as they vary with  $De$  are presented in Figure 26.

A steadily increasing trend with Dean number is evident. When compared with results from Bottaro, *et al.* [Ref. 10] for the same  $De$  and approximately same streamwise location, the present results are slightly lower. This is probably because of a slightly smaller measurement plane in the present study.

### 3. Longitudinal Reynolds Normal Stress

Variations of the longitudinal Reynolds normal stress with Dean number are presented in Figures 27 through 34. In Figures 27 through 30, the data is presented normalized by the local mean velocity squared whereas in Figures 31 through 34 the data is normalized by the bulk mean velocity squared. These data were obtained simultaneously with the mean velocity results presented earlier.

At low  $De$  ( $De < 150.6$ ), the values of longitudinal Reynolds normal stress are very low. This is because the values of turbulence intensity at the exit of the nozzle are also very low as previously discussed. In Figures 27 to 30, increases in Reynolds stress first occur at locations corresponding to inflow regions near the concave surface that are present between the two vortices which makeup each vortex pair. These stress regions first become apparent at  $De = 60.2$  and become more apparent as the Dean number increases. For some Dean numbers, as is seen at  $De = 90.4$ , two side by side regions of localized increased turbulence intensity are present within the location corresponding to one upwash region. This corresponds to regions of high mean shear on either side of an upwash. Here the mean velocity gradients in spanwise and radial directions are high.

For  $De$  above 150.6, the stress magnitude continuously increases with the highest intensity levels occurring within the upwash regions. Above  $De = 250.8$ , the intensity contours appear less periodic in the spanwise direction. Finally, at  $De = 263.3$  through 451.5 the contours become spanwise uniform. Such behavior corresponds to spanwise uniform streamwise mean velocity contours and velocity perturbation contours.

Results presented in Figures 27 through 30 are qualitatively similar to results presented in Figures 31 through 34. Normalizing by the local mean velocity tends to magnify Reynolds normal stress variations in regions of low velocity, such as exist near the concave wall in upwash regions.

Some notable features of these surveys are presented in Figures 35 through 42, where Reynolds normal stress variations are presented in dimensional form. Figure 35 presents the minimum and maximum values from each survey. Minimum values are representative of the flow for the range of  $Y/d$  from 0.1 to 0.8. For  $De = 50.2$  through 125.4, the values are initially very low. At  $De = 150.6$ , the magnitude of the maximum value increases dramatically in magnitude. This corresponds to the start of the twisting mode, a phenomena that appears as vortex patterns that rock [Ref. 4]. At a Dean number of 250.8, the magnitude of the maximum turbulence intensity again increases drastically and continues to increase through  $De = 451.5$ . The same trend is observed in the minimum value for  $De \geq 250.8$ .

Figures 36 through 39 present values of the dimensional longitudinal turbulence intensity for specific locations within vortex pair structures. These locations were selected to correspond to specific locations within the left most upwash region seen in the survey shown in Figure 16. Values of the longitudinal normal stress are given in Figure 36 for locations where this quantity is a maximum. Values of the longitudinal normal stress are given in Figure 37 for  $Y/d = 0.1$  at the same  $Z/d$  position where the maximum occurs. Values of the longitudinal normal stress are given in Figure 38 for the channel centerline ( $Y/d = 0.5$ ) at the same spanwise locations as Figures 36 and 37. Figure 39 presents the value at a fixed radial and spanwise location ( $Y/d = 0.1$  and  $Z/d = 5.2$ ). This location corresponds to the location of the maximum intensity for  $De = 100.4$ . The general trends are similar to those observed in Figure 35.

Figures 40 through 42 present composites of the data shown previously in Figures 36 through 38. The dimensional longitudinal Reynolds stress variations in these figures are given for three different locations within the vortex pair structure: within an inflow region near the local streamwise mean velocity minima at  $Y/d = 0.1$ , within an inflow region at  $Y/d = 0.5$  and the same  $Z/d$  position, and at the location where the longitudinal normal stress is maximum. The data in these figures thus correspond to specific locations within the vortex pair structure and not to fixed  $Z/d$  locations as  $De$  is changed.

Figure 40 indicates that dimensional normal stress magnitudes increase with  $De$ , and are quite low for  $De < 150$ . For  $De$  from 50 to 75, magnitudes at  $Y/d = 0.5$  are higher than ones for  $Y/d = 0.1$ , whereas the opposite trend is generally present for higher  $De$  up to 125. When normalized using  $U_{bulk}$ , maximum  $\overline{u'^2}$  magnitudes vary between 0.019 and 0.028.

As  $De$  increases above about 150, Figure 41 (which includes the Figure 40 data plotted using different abscissa and ordinate scales) shows that  $\overline{u'^2}$  magnitudes are much higher than those at lower  $De$  for all three locations within the vortex pair structure. Compared to results at  $De = 125$ , longitudinal normal stress magnitudes are about 30 times greater. According to Ligrani, *et al.* [Ref. 8], these higher stresses at  $150 \leq De \leq 185-200$  are probably mostly due to twisting motions of the vortex pairs, as well as a partial result of fluid that, in some cases, may be agitated by twisting. Twisting is believed to be associated with turbulent energy increases because both occur at the same locations within a vortex pair structure and over nearly the same range of Reynolds numbers.



### C. NEAR WALL PROFILES

Near wall profiles of the streamwise mean velocity and the longitudinal Reynolds normal stress are presented in Figures 43 through 63. These results were obtained using single-sensor hot-wire probes mounted on DISA type 55P04 probe mounts. At the beginning of each profile, each probe is initially located at an approximate radial position of  $Y = 0.015$  inches (i.e., 0.015 inches from the concave wall). Individual probes are then moved away from the concave wall in 0.005 inch steps, as previously discussed. Measurements are taken at three spanwise locations ( $Z/d = 5.25, 5.50$  and  $6.00$ ) for  $De = 125, 170, 240$  and  $401$ .

These spanwise locations and  $De$  were selected based upon the surveys presented earlier in Figures 16 to 19. The first spanwise position,  $Z/d = 5.25$ , was chosen because it corresponds to a position near the center of the left most upwash region for  $De = 125.4$  in Figure 16. The second spanwise position,  $Z/d = 5.50$ , corresponds to a position just to the right of the same upwash region. The third and final spanwise position,  $Z/d = 6.00$ , corresponds to a downwash region. Of course, these positions with respect to vortex pair structure were expected to be slightly different for other  $De$  of 170, 240 and 400.

The lowest velocity measured in these profiles is above values corresponding to  $Re_d = 0.07$ , the mixed convection limit for hot-wire probes given by Ligrani and Bradshaw [Ref. 19]. This  $Re_d$  is based on local mean velocity and sensor wire diameter. For the presently employed sensors, the  $Re_d$  value corresponds to a fluid velocity of approximately 0.2 m/s. Above this mean velocity, the probe is subject to forced convection only.

#### 1. Streamwise Mean Velocity

Near wall streamwise mean velocity profiles are presented in Figures 43 through 49. Data for  $De = 125$  are presented in Figures 43 and 44, for  $De = 170$  in Figure

45, for  $De = 240$  in Figure 46 and for  $De = 401$  in Figures 47 through 49. For  $De = 125$ , 170 and 240, data are presented for all three spanwise positions. For  $De = 401$ , data are presented for  $Z/d = 5.25$  only because the flow at this  $De$  is spanwise uniform.

Magnitudes of the streamwise mean velocity given in Figure 43 are not in full agreement with surveys presented for the same  $De$  in Figure 16. These differences are not presently fully understood. They may be a result of movement of the vortex pairs relative to positions evident in the surveys or because of data scatter resulting from the difficulties in measuring the very low flow velocities at this  $De$ .

The data of Figure 43 are also plotted in wall coordinates in Figure 44. The wall coordinates are given by:

$$u^+ = \frac{u}{u_\tau} \quad \{4.2\}$$

and:

$$y^+ = \frac{Y u_\tau}{\nu} \quad \{4.3\}$$

where:

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}} \quad \{4.4\}$$

where  $\tau_w$  is the shear stress at the wall,  $u_\tau$  is the friction velocity,  $\nu$  is the kinematic viscosity and  $\rho$  is the fluid density. The quantity  $\tau_w/\rho$  was determined using the relationship:

$$\frac{\tau_w}{\rho} = \nu \left. \frac{\partial u}{\partial y} \right|_{y \rightarrow 0} \quad \{4.5\}$$

where  $\partial u / \partial y|_{y \rightarrow 0}$  is the velocity gradient near the wall. This quantity was determined experimentally using the data from Figure 43 for  $Y/d \leq 0.1$ . The values of  $u_\tau$  determined by this method for  $De = 125$  were 0.083 m/s, 0.068 m/s and 0.061 m/s for  $Z/d = 5.25$ , 5.50 and 6.00, respectively. By comparing the data plotted in these coordinates with the theoretical relationship  $u^+ = y^+$ , errors in the initial radial positions of the probe were determined. Magnitudes of these errors were determined from  $De = 125$  data for each  $Z/d$ , then applied to near wall results at all  $De$  studied.

Data for  $De = 170$  shown in Figure 45 show better consistency with survey results than the near wall profile at  $De = 125$ . However, some differences are still apparent that may be due to shifting of the spanwise position of vortex pairs. The profile for  $De = 240$  in Figure 46 shows good consistency with survey data in Figure 18 for the same  $De$ . In both figures,  $Z/d = 5.50$  appears to correspond to an upwash region where velocities are lower and velocity gradients are higher than that at other spanwise locations and  $Z/d = 6.00$  appears to correspond to a downwash region where velocities are generally lower than at other spanwise locations.

Data for  $De = 401$  are presented in Figures 47 through 49. Figure 47 shows a profile that is similar to the turbulent survey results in Figure 19. The data are plotted in wall coordinates in Figures 48 and 49 using a friction velocity for normalization determined from a Clauser [Ref. 25] plot. With the Clauser plot,  $u^+y^+$  is first determined using the equation given by:

$$u^+y^+ = \frac{u Y}{v} \quad \{4.6\}$$

$y^+$  is then determined using the relationship:

$$u^+y^+ = y^+ \left[ \frac{1}{0.41} \ln y^+ + 5.2 \right] \quad \{4.7\}$$

With  $y^+$  known, the friction velocity is then calculated by:

$$u_\tau = \frac{y^+ \nu}{Y} \quad \{4.8\}$$

Using this technique, the friction velocity is 0.222 m/s for the  $De = 401$  data at  $Y/d = 0.1$ . With this friction velocity used to normalize the streamwise mean velocities, Figures 48 and 49 show good agreement with the law-of-the-wall for  $y^+ > 30-35$ . For lower  $y^+$ , the data deviated from the law-of-the-wall in the buffer region of the boundary layer, as expected.

## 2. Longitudinal Reynolds Stress

Longitudinal Reynolds stress results are presented in Figures 50 through 63 for the same  $De$  and  $Z/d$  as the streamwise mean velocity data. Figures 50 through 53 present the dimensional longitudinal Reynolds normal stress. Figures 54 through 57 present the same data normalized by the local mean velocity squared. Figures 58 through 61 present the data normalized by the bulk velocity. Figures 62 and 63 compare the results for  $De = 401$  with results by Kreplin and Eckelmann [Ref. 26], Moser and Moin [Ref. 9] and Morrow [Ref. 27].

As with the mean velocity profiles, the longitudinal turbulence intensity data for  $De = 125$  and 170 are not consistent with the survey data. These inconsistencies probably result for the same reasons that the inconsistencies between the streamwise mean velocity surveys and the streamwise mean velocity profiles are present. At  $De = 240$  and 401, profile results are in good agreement with the data from the surveys.

Figure 62 shows that the present results are in excellent agreement with ones from Kreplin and Eckelmann [Ref. 26] and Moser and Moin [Ref. 9], particularly for  $y^+ > 18$ . For  $y^+ < 18$ , the results from the present study are somewhat lower, probably because the data obtained from Refs. 26 and 9 were obtained in channel flows at higher

Reynolds numbers. The magnitude of  $Re_\tau$  for Ref. 26 is 195, where  $Re_\tau$  is the Reynolds number base on friction velocity and channel half-height,  $\delta$ . The magnitude of  $Re_\tau$  for Ref. 9 is 168. The present measurements correspond to a less developed, or younger, boundary layer at  $Re_\tau = 90.3$ . In younger boundary layers, the peak in turbulence intensity typically occurs at a greater  $y^+$  than for boundary layers at higher  $Re_\tau$ .

In Figure 63, the results for  $De = 401$  are compared with results obtained by Morrow [Ref. 27] in a straight channel flow with identical channel cross-section and inlet geometry, and similar flow conditions. Morrow's results are lower than the ones obtained in the curved channel, primarily because of the manner in which electronic signals are sampled and processed in the two studies. In Morrow's study, the output from the hot-wire was sampled at 100 Hz and 200 Hz with appropriately set anti-aliasing filters. Therefore, some of the higher frequency components of the signal are not included in the magnitudes of Morrow's  $\overline{u'^2}$  data presented in Figure 63.

### C. EFFECT OF CHANNEL CLEANING

Figures 116 through 119 are presented to illustrate the effects of channel cleaning on measured distributions of streamwise mean velocity and longitudinal Reynolds normal stress. These data were obtained at a time when some dirt and dust was present at the channel inlet. As previously discussed, the channel was cleaned immediately prior to the measurement of survey results presented earlier.

Figures 116 and 117 present the dimensional streamwise mean velocity prior to channel cleaning for  $De = 125.4$  and 175.6. Figures 118 and 119 present the longitudinal Reynolds normal stress under the same conditions. By comparing these figures with similar results obtained after the channel was cleaned (Figures 70, 73, 96 and 99, respectively), it is evident that streamwise mean velocity data are very similar, except that

the locations of individual vortex pairs are shifted in the spanwise direction. More significant changes to the qualitative distributions of longitudinal Reynolds normal stress are apparent since magnitudes are reduced by a factor of 10 in the clean channel at  $De = 125.4$  and  $De = 175.6$ . At higher  $De$ , channel cleaning had little effect on distributions of streamwise mean velocity or longitudinal Reynolds normal stress.

## V. SUMMARY AND CONCLUSIONS

A transparent curved rectangular channel with 40 to 1 aspect ratio was utilized to investigate variations of streamwise mean velocity and longitudinal turbulence intensity that occur at different locations in a spanwise/radial plane located 120 degrees from the start of curvature over a range of Dean numbers. To obtain these measurements, a single-sensor hot-wire probe was traversed over a plane of 328 data points (in a 41 by 8 grid) using an automated two-dimensional traversing apparatus. With a slightly modified version of the same traverse, near-wall profiles of streamwise mean velocity and longitudinal Reynolds normal stress were also obtained.

At a Dean number of 50.2, streamwise mean velocity surveys show spanwise uniform behavior. As the Dean number increases, evidence of Dean vortex pairs is apparent and the flow becomes spanwise periodic due to streamwise velocity deficits at upwash regions located between the two vortices that make up each vortex pair. As the Dean number increases above 263.3, evidence of Dean vortex pairs is less apparent as the flow becomes more or less spanwise uniform.

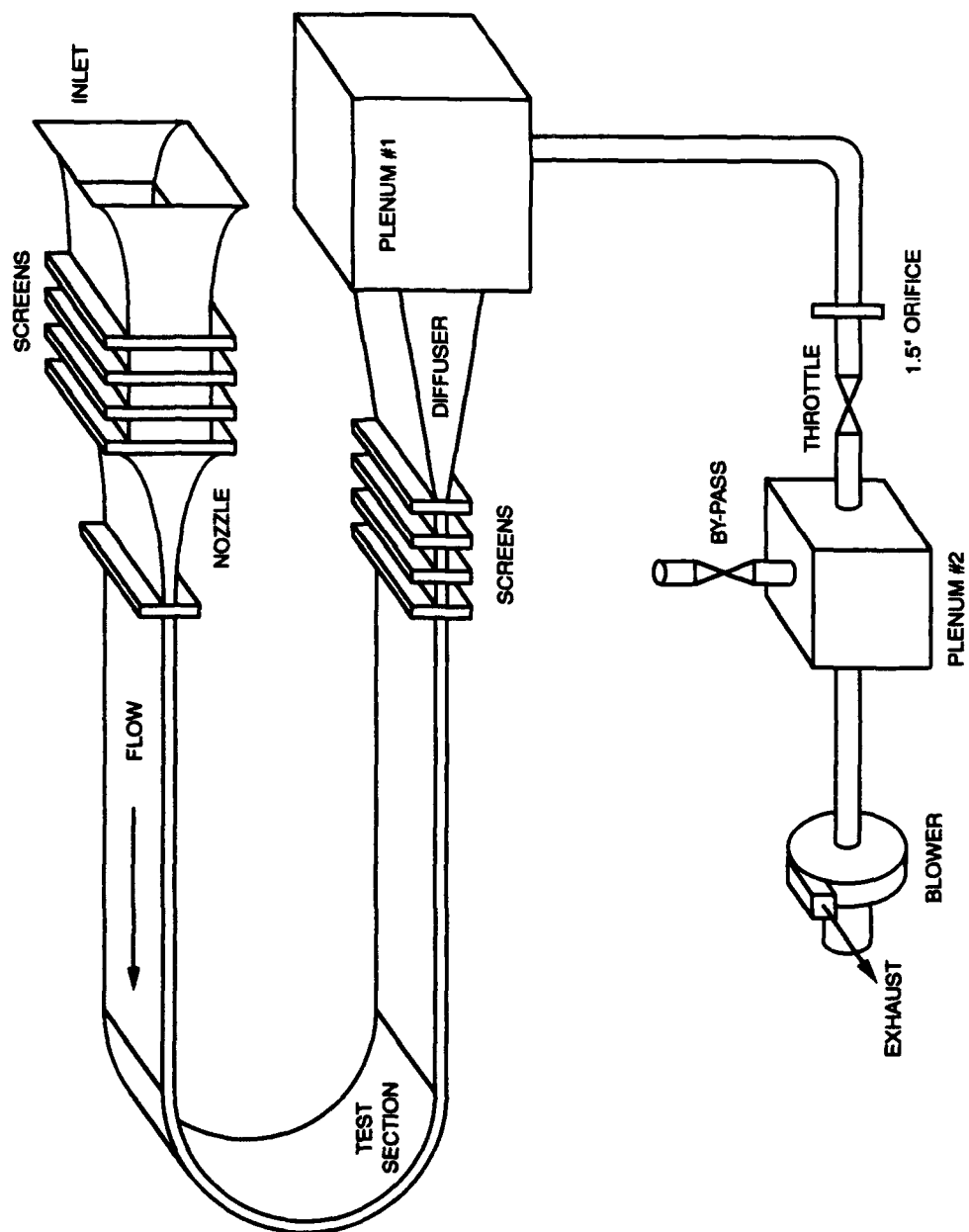
Longitudinal Reynolds normal stress survey results show locally higher magnitudes for Dean numbers above 60.2 that initially occur at locations corresponding to inflow regions near the concave surface. As the Dean number is increased further, stress magnitudes within the upwash regions continuously increase. As the Dean number becomes greater than 150.6, results show that the stress magnitudes are much greater than at lower Dean numbers. Such increases correspond closely with twisting vortex motions, which is important in regard to transition from laminar to turbulent flow because these variations provide evidence that twisting results in the first important increases in turbulence energy at a given location as the Dean number increases. As the Dean number

exceeds 263.3, regions of locally higher stress merge together to form a fully turbulent flow with spanwise uniform distributions of longitudinal Reynolds normal stress.

Near wall profiles of streamwise mean velocity and longitudinal Reynolds normal stress are in good agreement with survey data and with results from the literature for Dean numbers of 240 and 401. At a Dean number of 401, the streamwise mean velocity profile shows agreement with the law-of-the-wall for  $y^+ > 30$ . At lower Dean numbers, inconsistencies between profiles and survey data are believed to be due to differences in small scale disturbances resulting from dust build-up on the channel walls and inlet flow management apparatus.



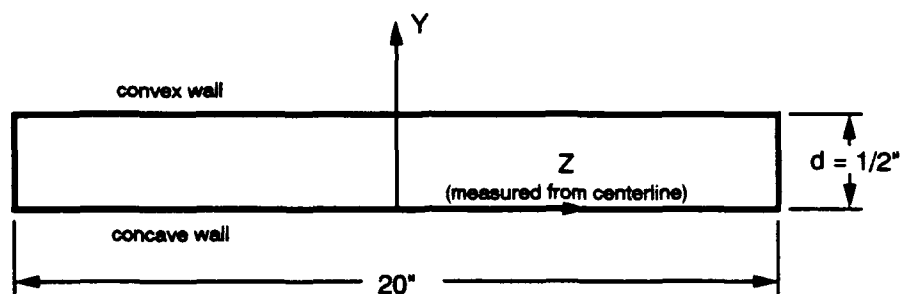
## APPENDIX A. FIGURES



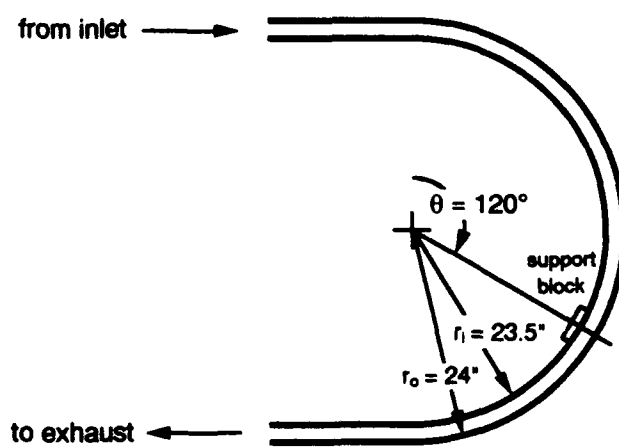
**Figure 1. Schematic of Test Facility**



**Figure 2. Test Facility (Side View)**

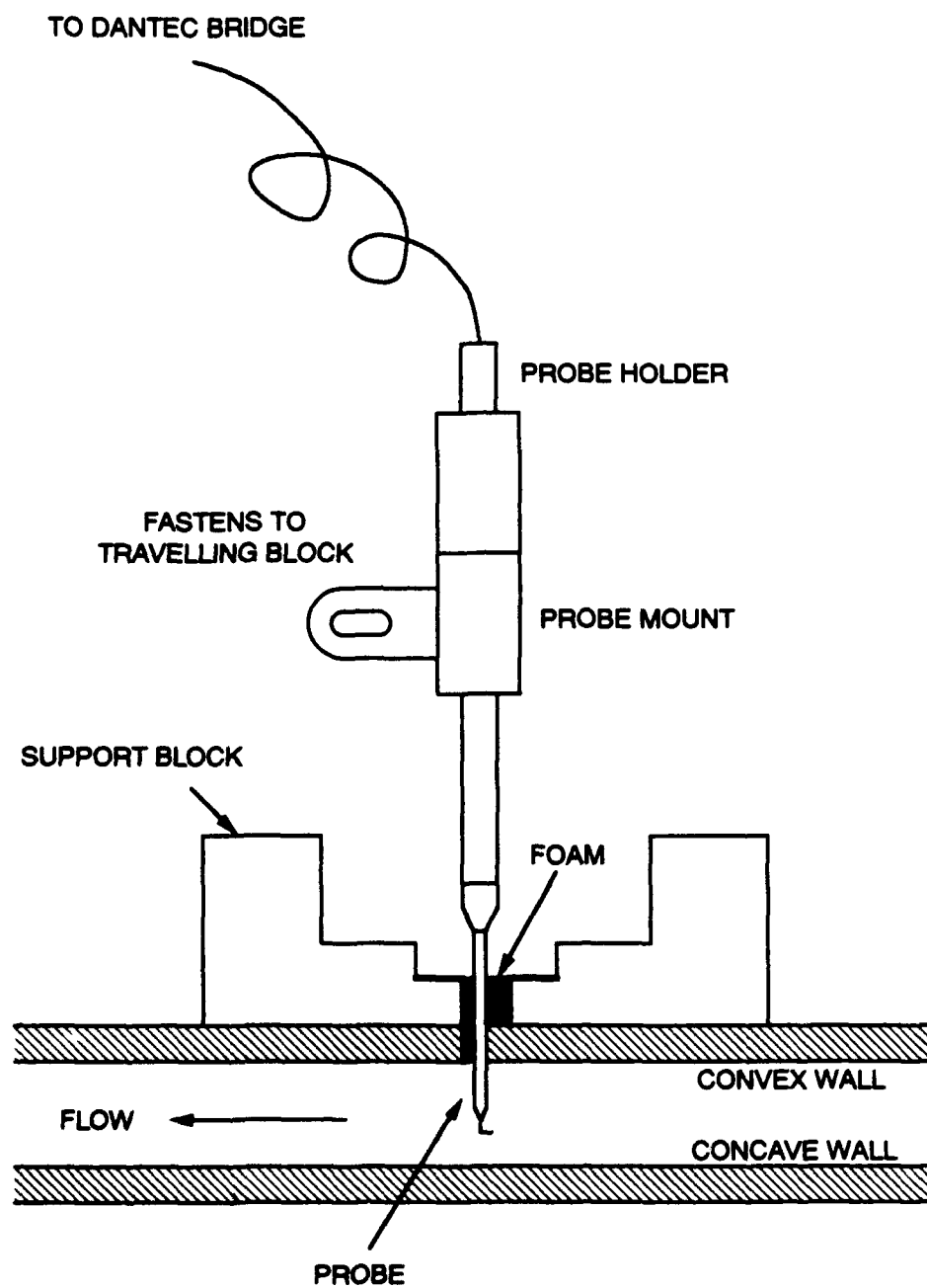


(a) Cross Section (not to scale)



(b) Test Section Geometry

Figure 3. Details of Test Section



**Figure 4. Schematic of Support Block**



**Figure 5. Detail of Support Block and Probe Mount Assembly**

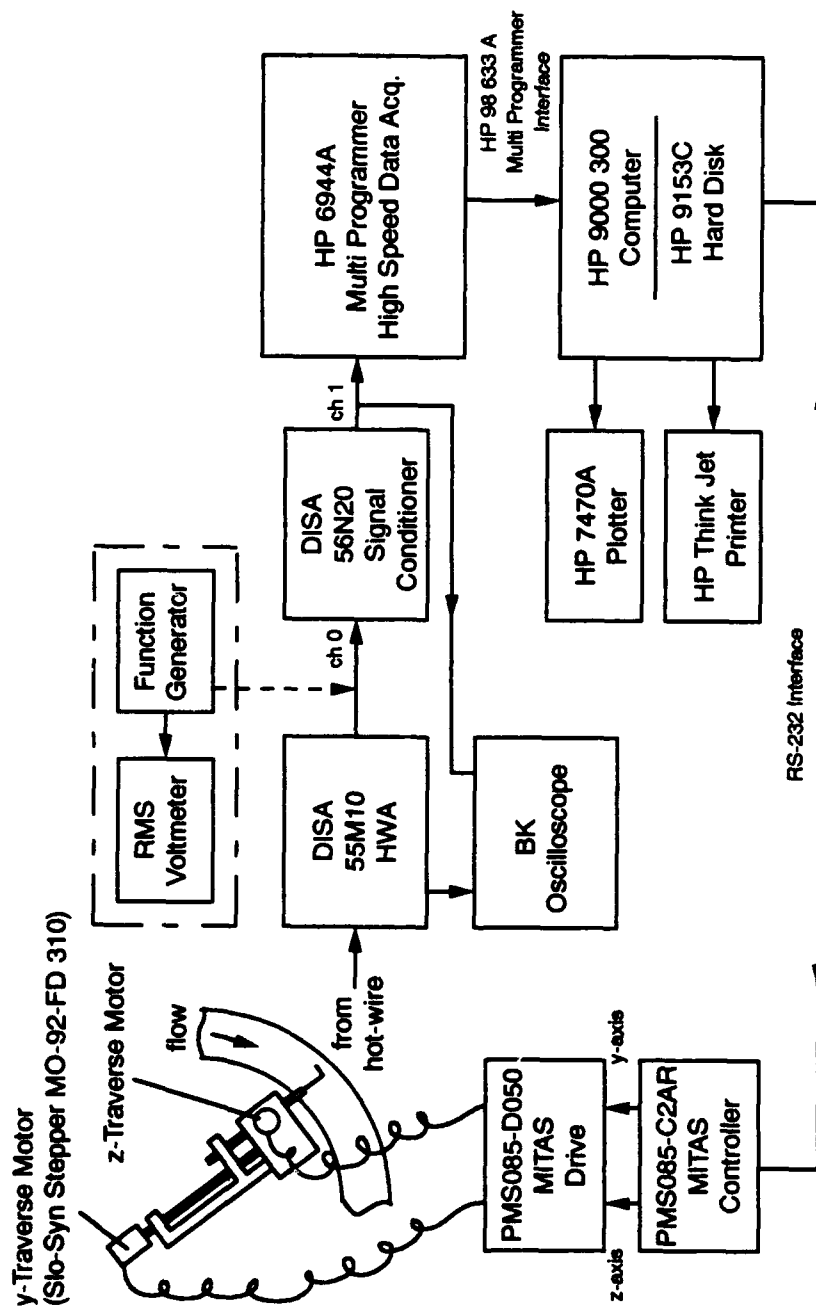
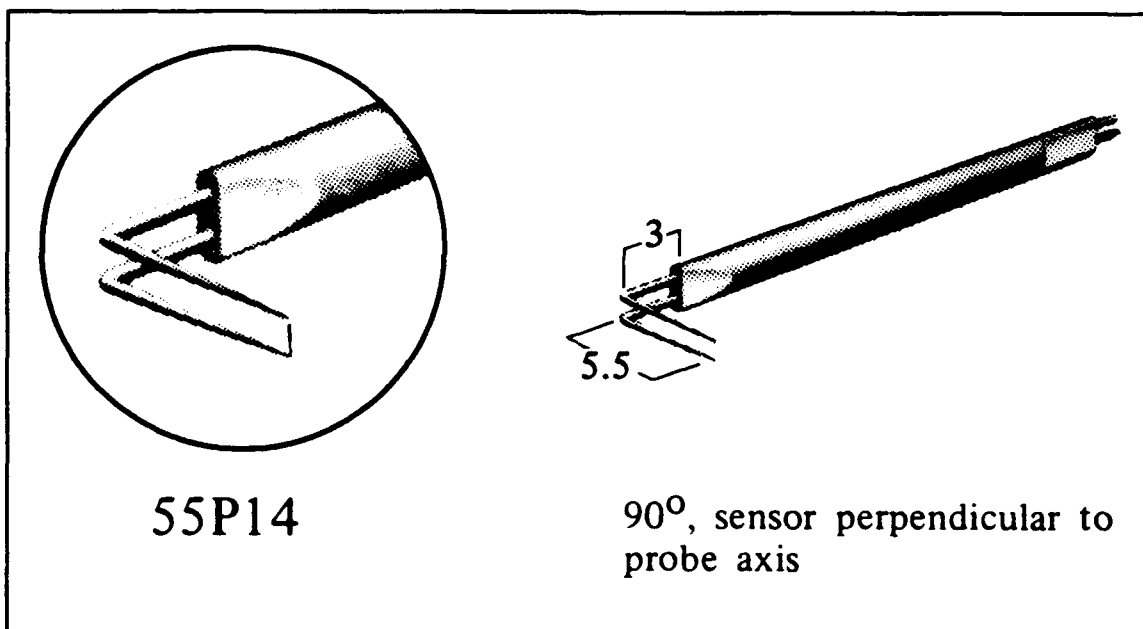
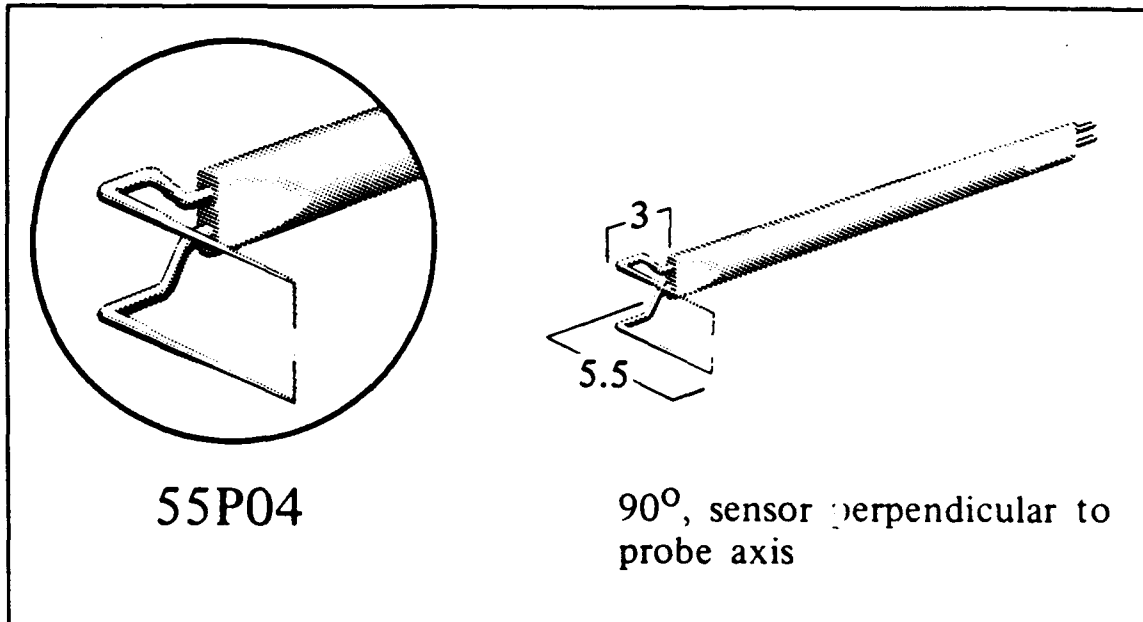
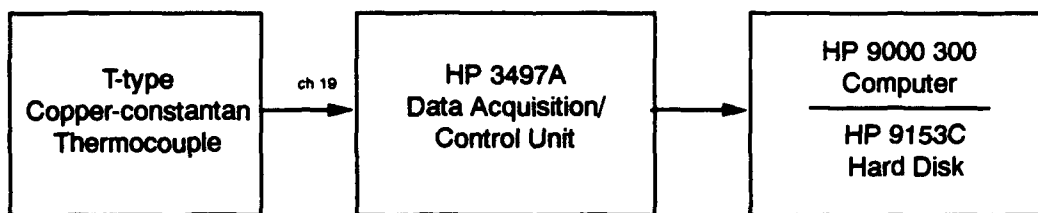


Figure 6. Data Acquisition System

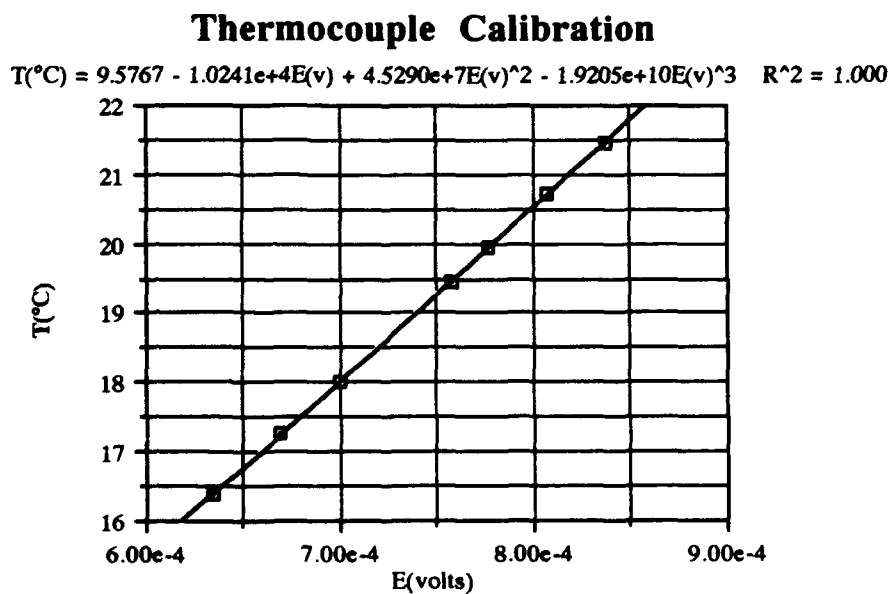


**Figure 7. Single-sensor Hot-wire Probes**





**Figure 8. Temperature Measurement System**



**Figure 9. Thermocouple Characteristics**



**Figure 10. Traverse Used for Velocity Surveys**



**Figure 11. Detail of Traversing Block Used for Velocity Surveys**



**Figure 12. Traverse Used for Near Wall Profiles**



**Figure 13. Detail of Traversing Block Used for Near Wall Profiles**

# Hot-Wire Calibration

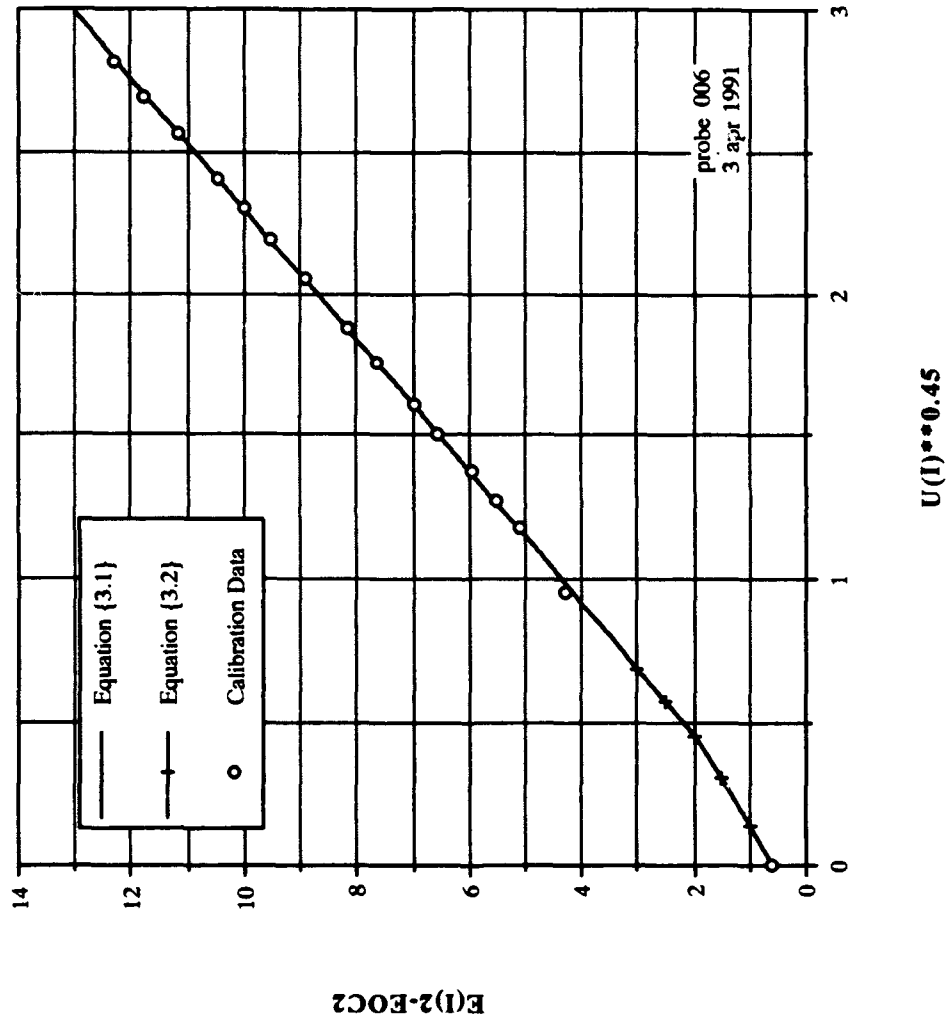


Figure 14. A Typical Hot-wire Calibration

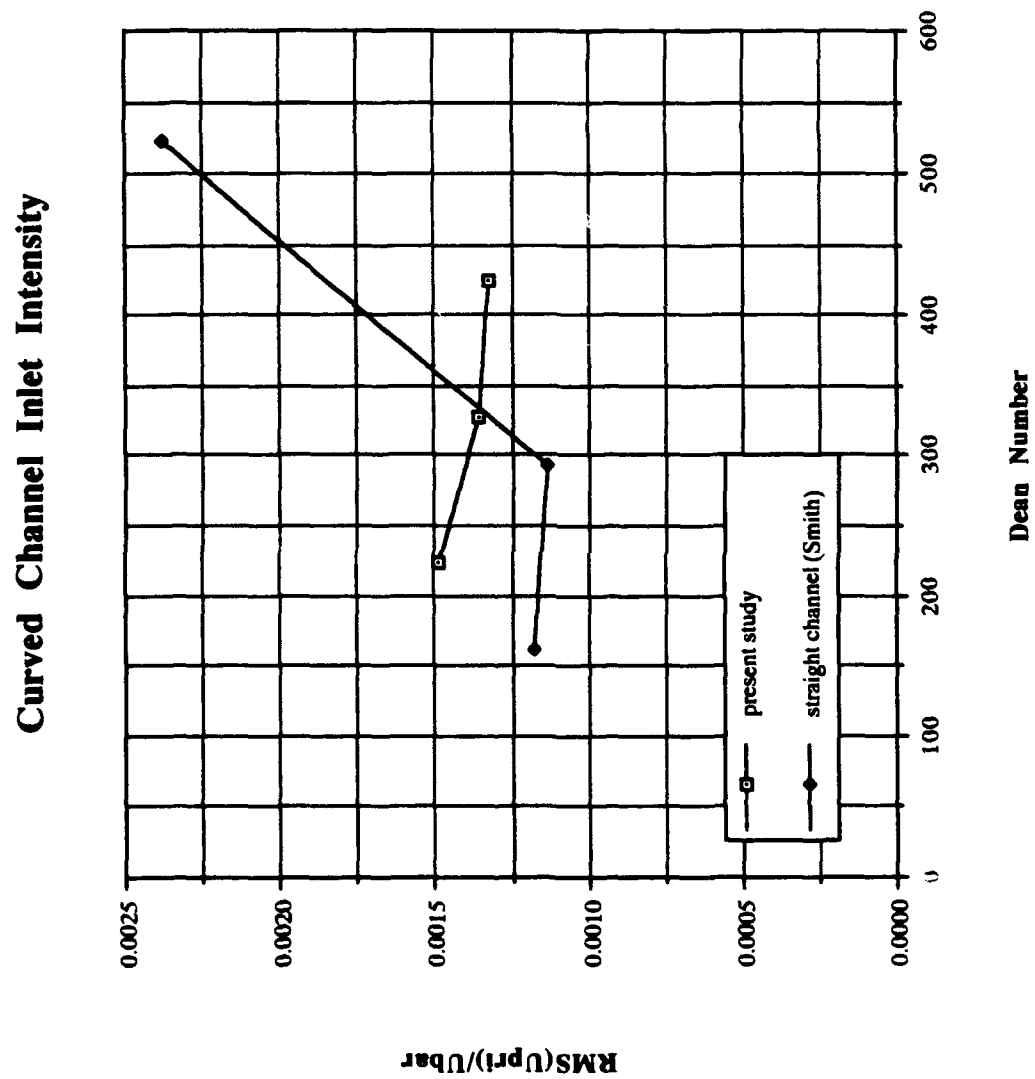


Figure 15. Inlet Turbulence Intensities

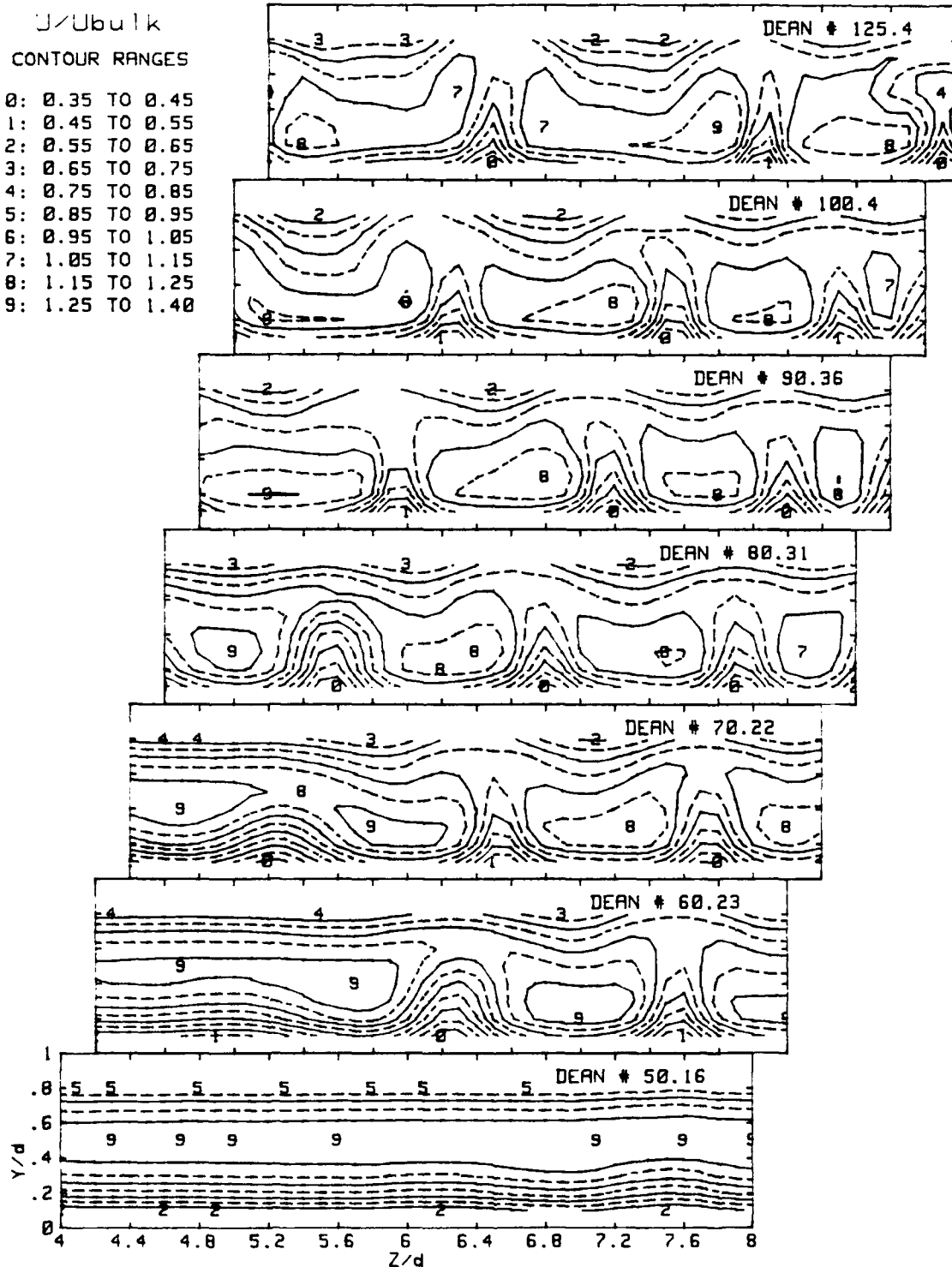


Figure 16. Streamwise Mean Velocity Contours,  $De=50.2$  to  $De=125.4$



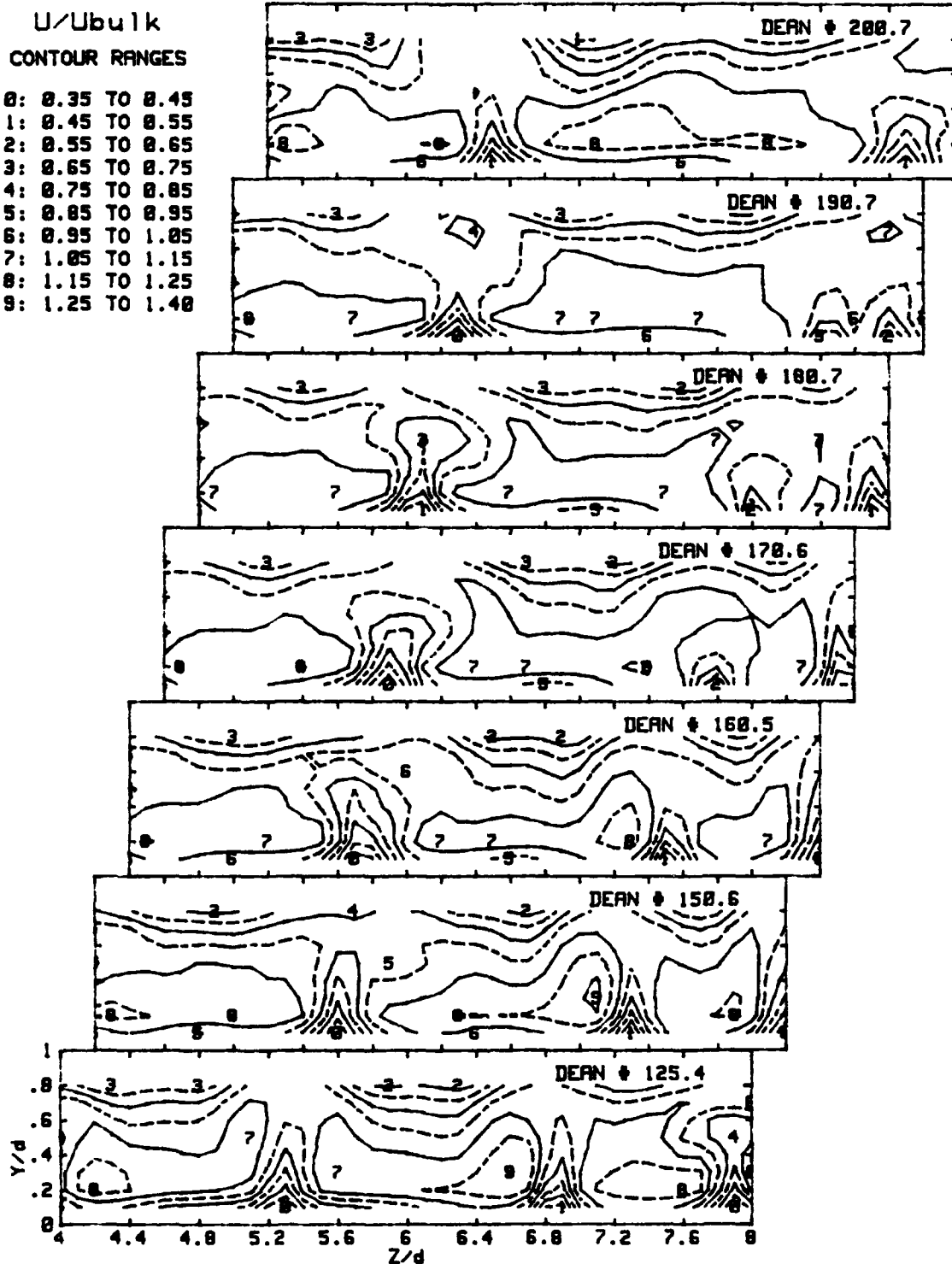


Figure 17. Streamwise Mean Velocity Contours,  $De=125.4$  to  $De=200.7$

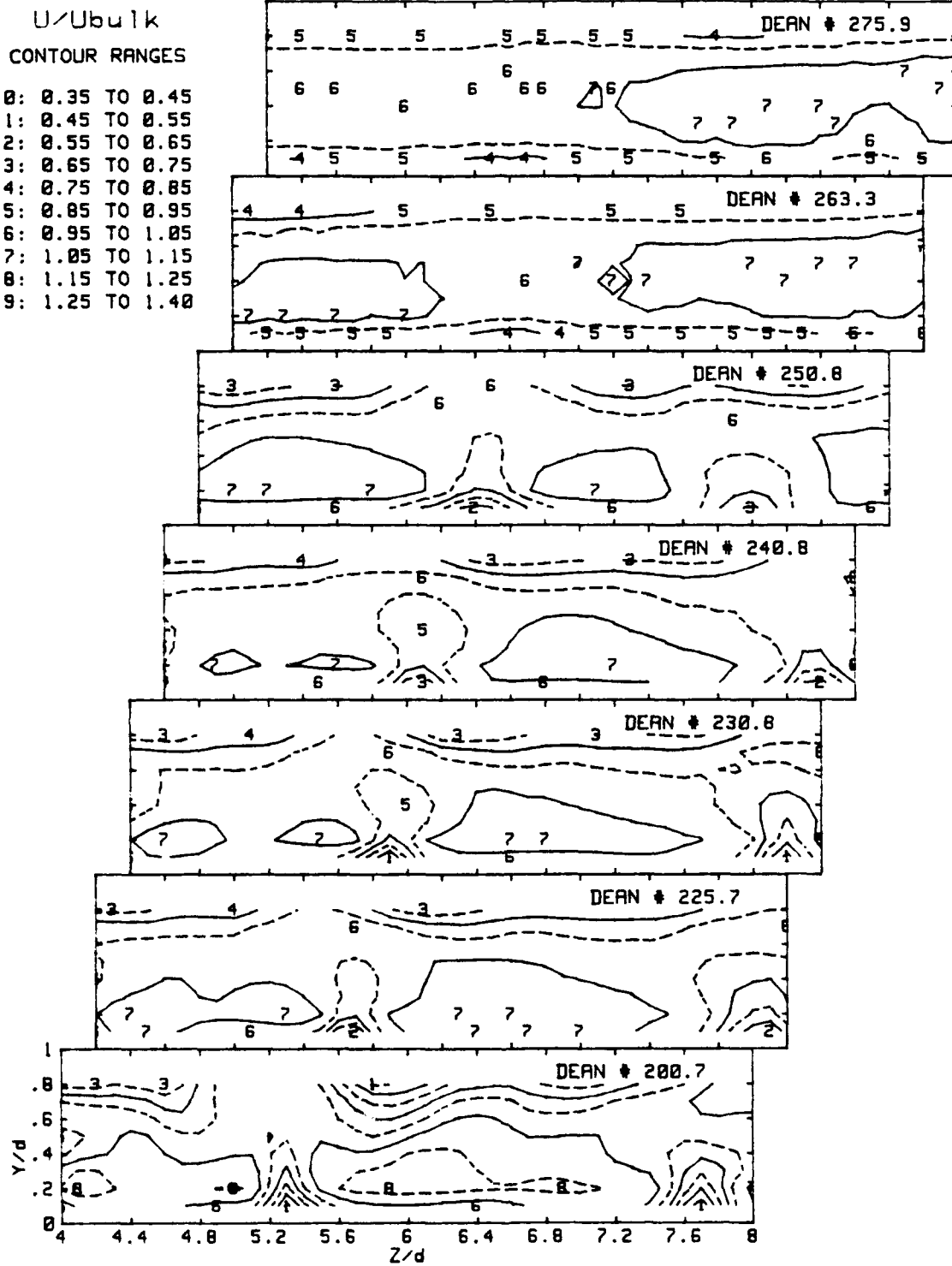


Figure 18. Streamwise Mean Velocity Contours,  $De=200.7$  to  $De=275.9$

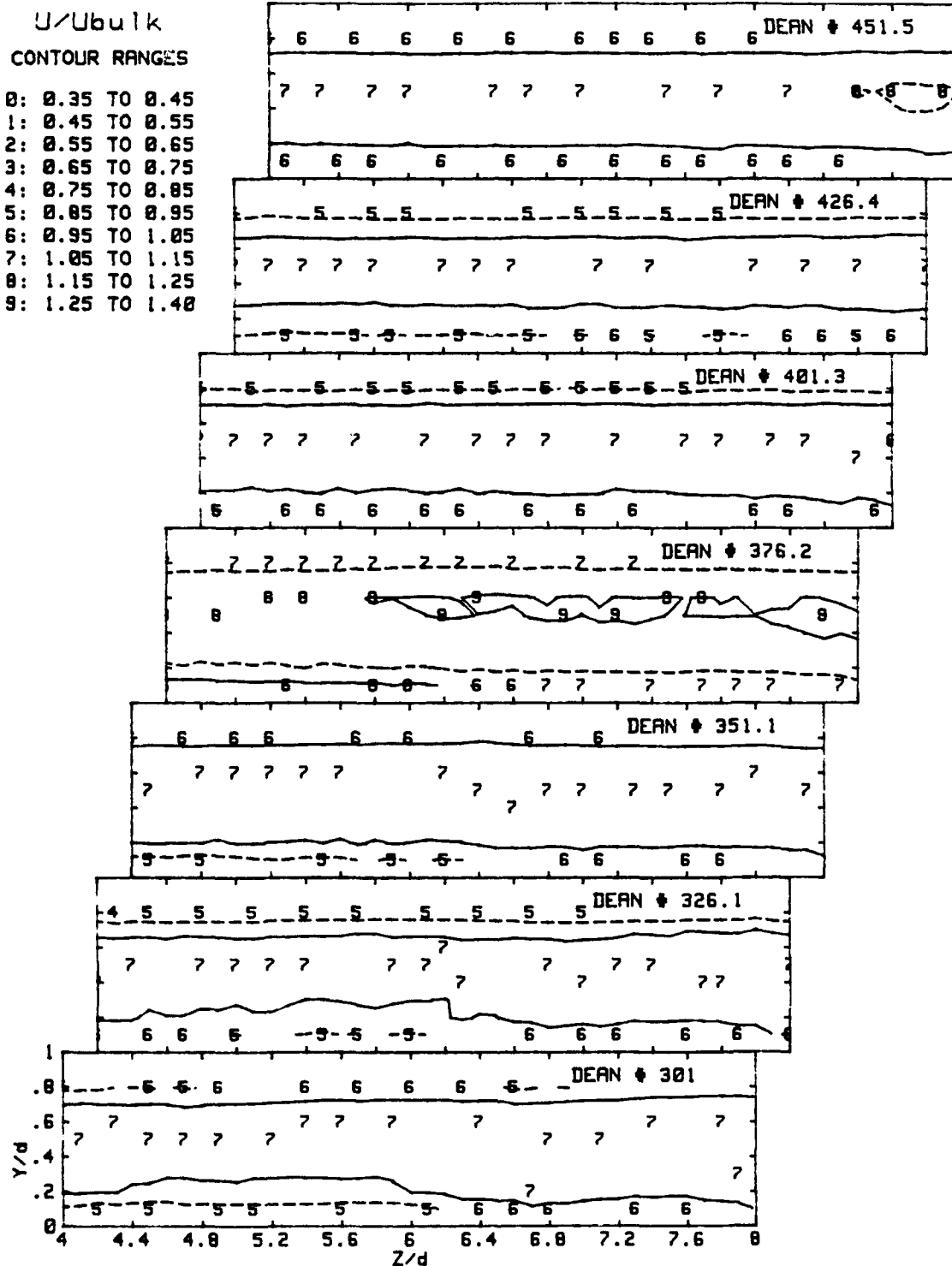


Figure 19. Streamwise Mean Velocity Contours,  $De=301.0$  to  $De=451.5$

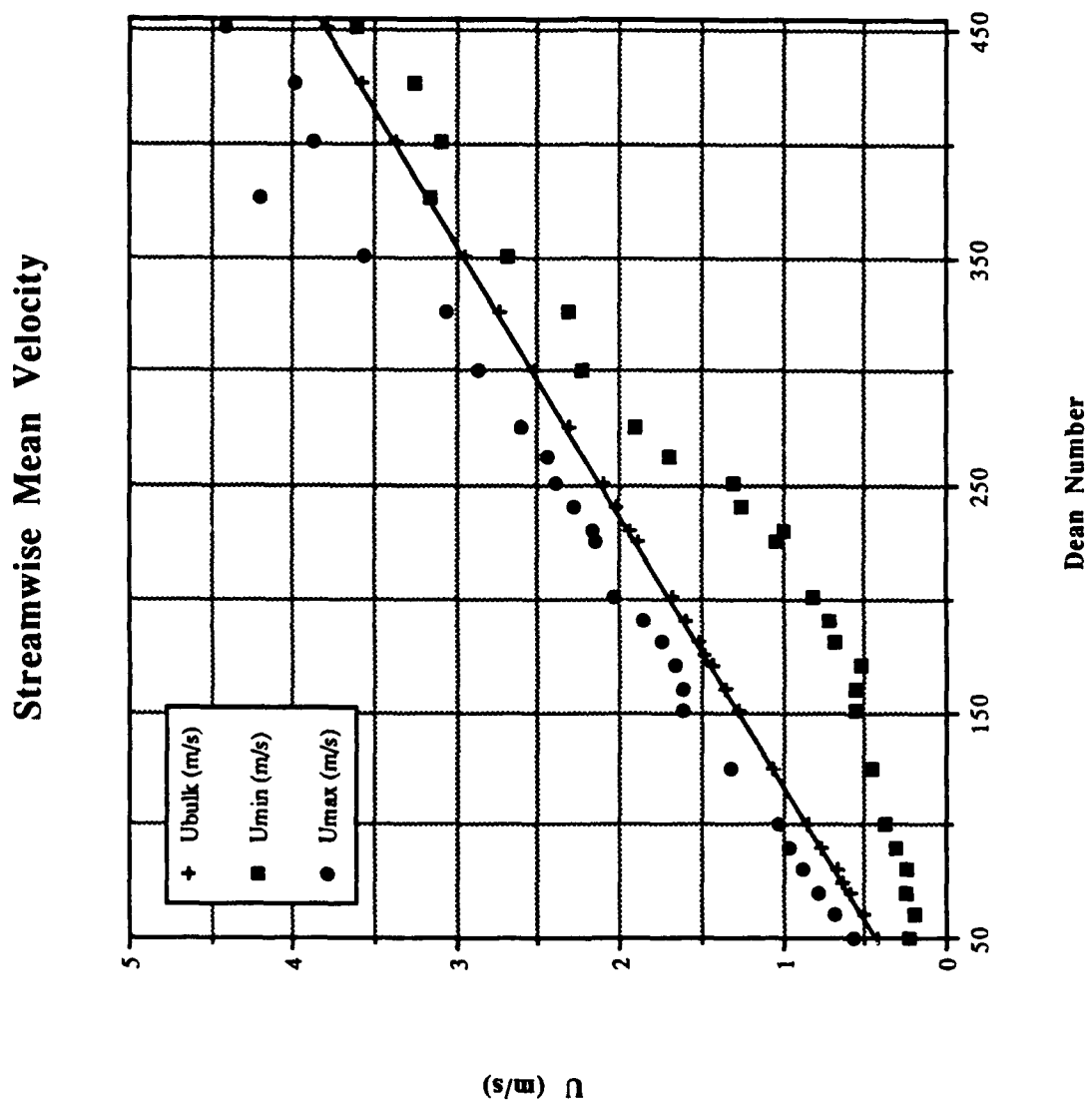


Figure 20. Maximum and Minimum Streamwise Mean Velocities,  
 $De=50.2$  to  $De=451.5$

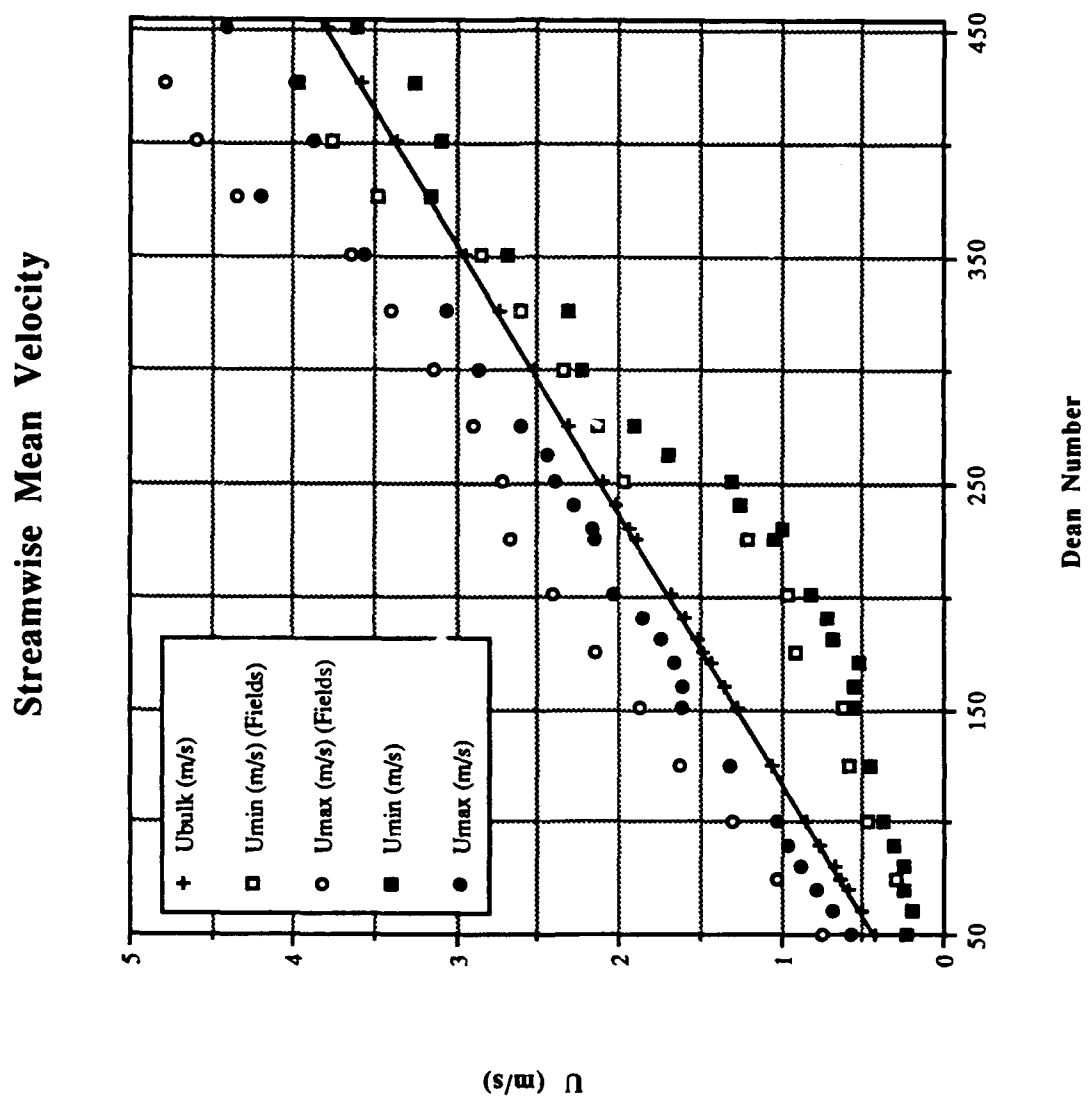


Figure 21. Maximum and Minimum Mean Velocities as Compared With Fields (1990)

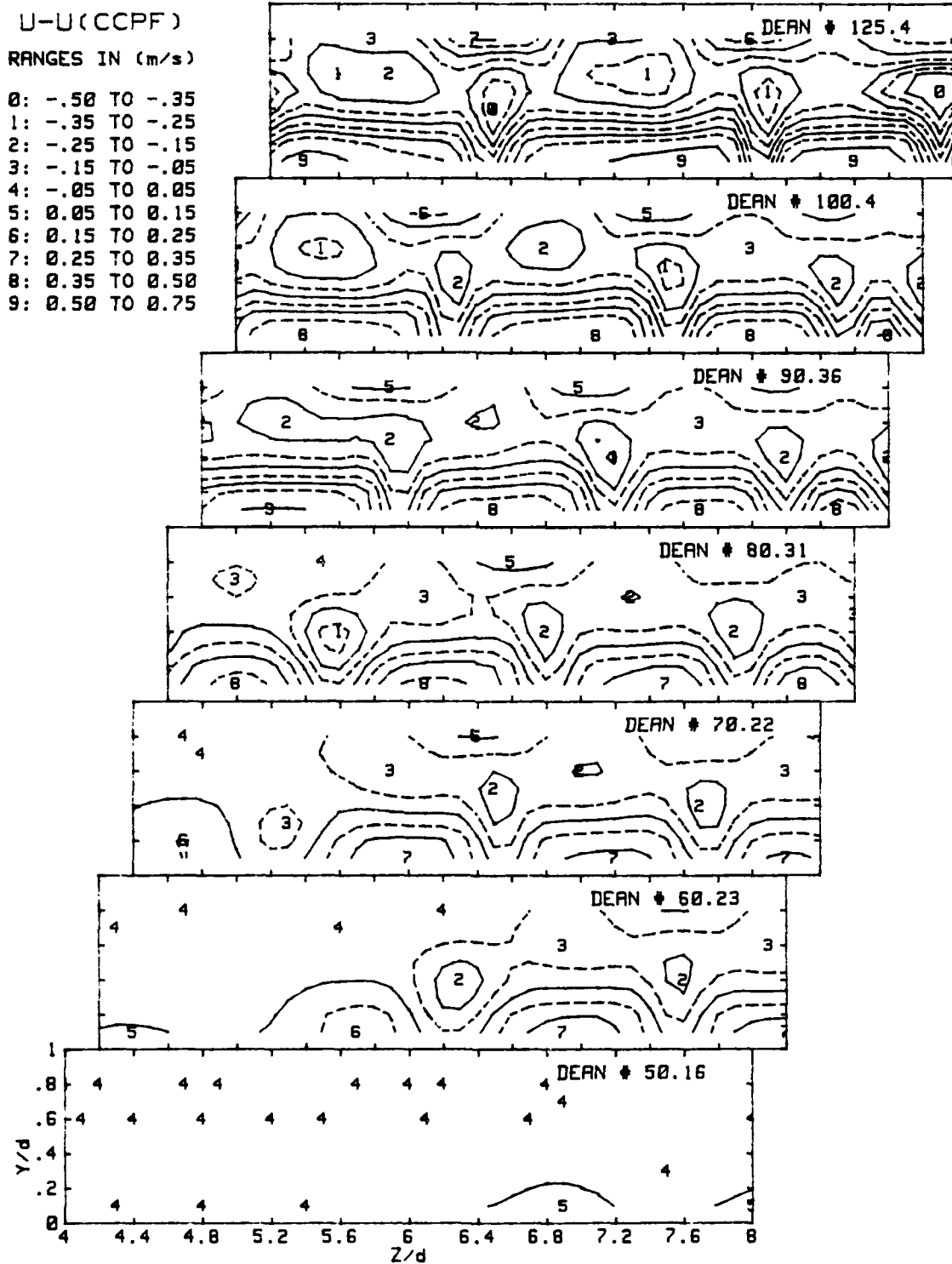


Figure 22.  $\bar{u} - u_{CCPF}$  Contours,  $De=50.2$  to  $De=125.4$

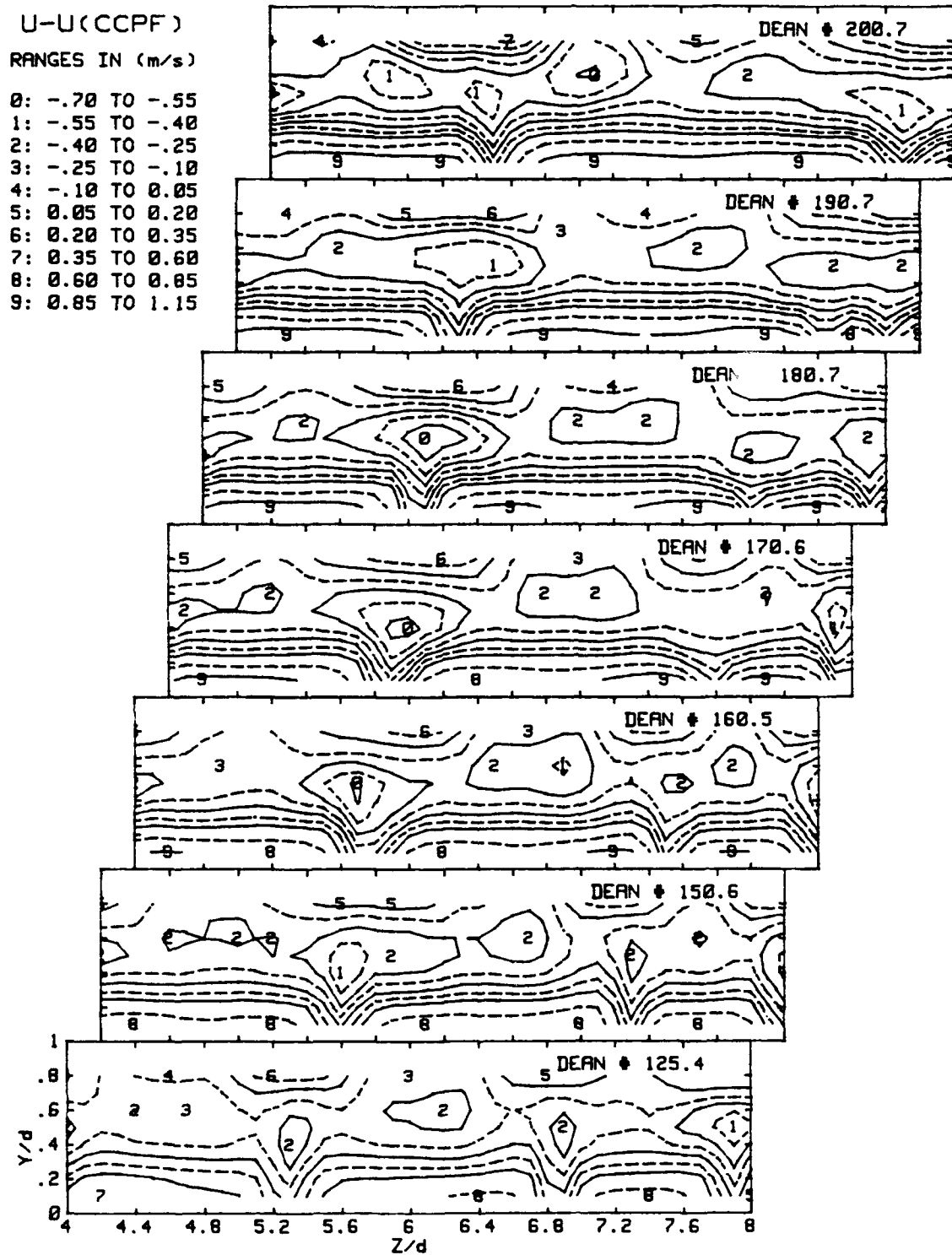


Figure 23.  $\bar{u} - u_{CCPF}$  Contours,  $De=125.4$  to  $De=200.7$

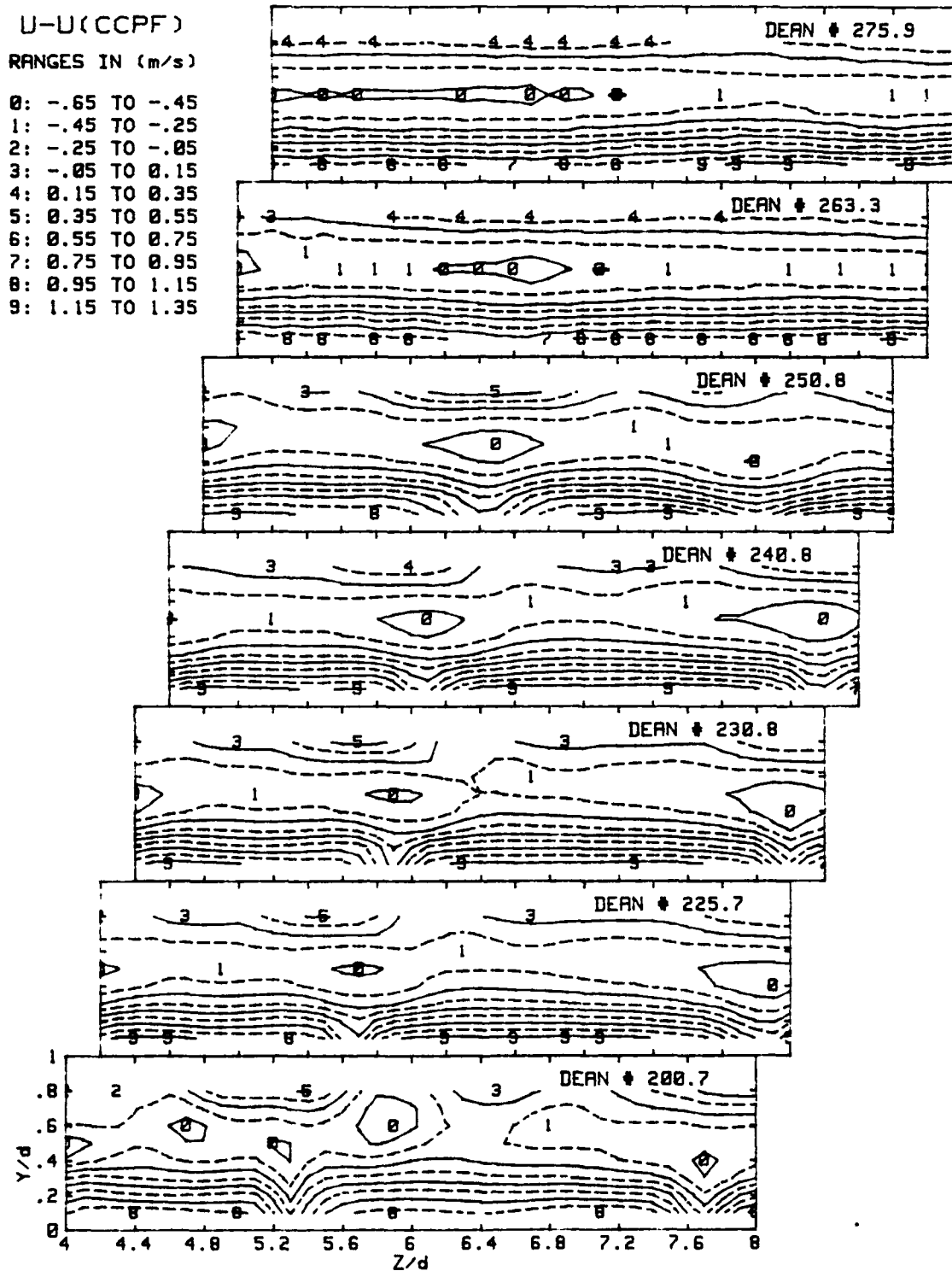


Figure 24.  $\bar{u} - u_{CCPF}$  Contours,  $De=200.7$  to  $De=275.9$



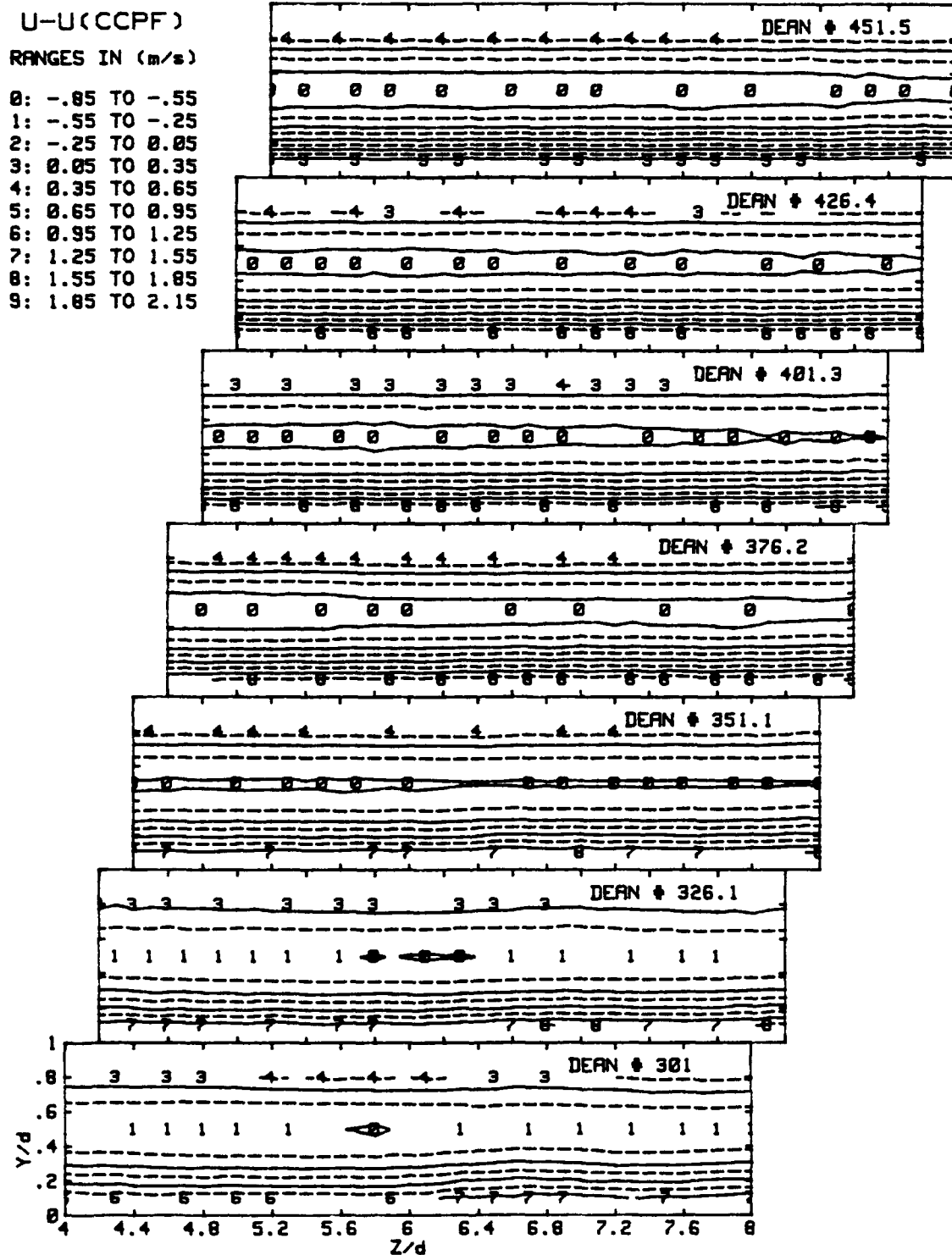


Figure 25.  $\bar{u} - u_{CCPF}$  Contours,  $De=301.0$  to  $De=451.5$

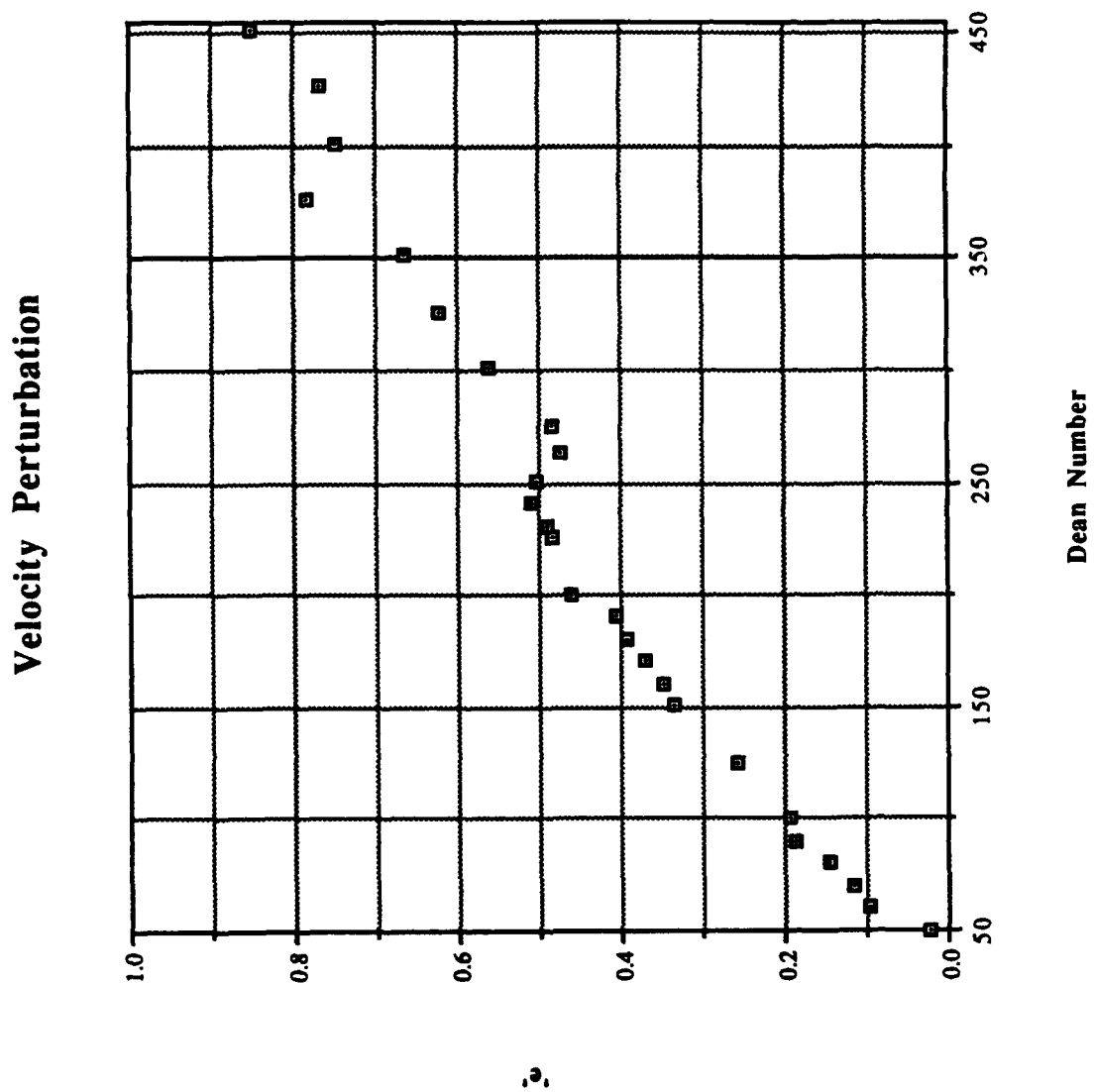
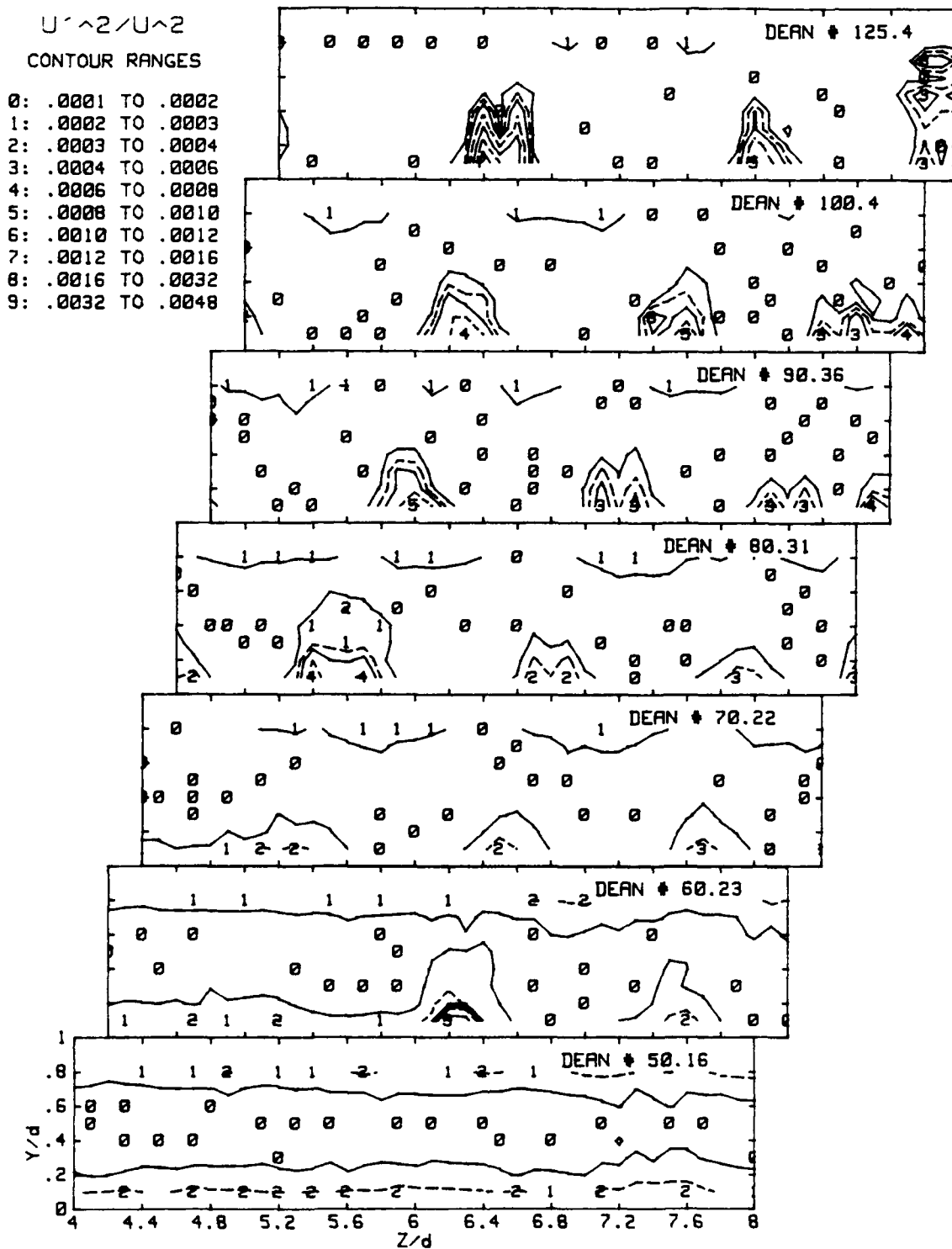


Figure 26. Streamwise Velocity Perturbation,  $e_s$ , vs Dean Number



**Figure 27. Longitudinal Reynolds Normal Stress Normalized by the Local Mean Velocity Squared,  $De=50.2$  to  $De=125.4$**

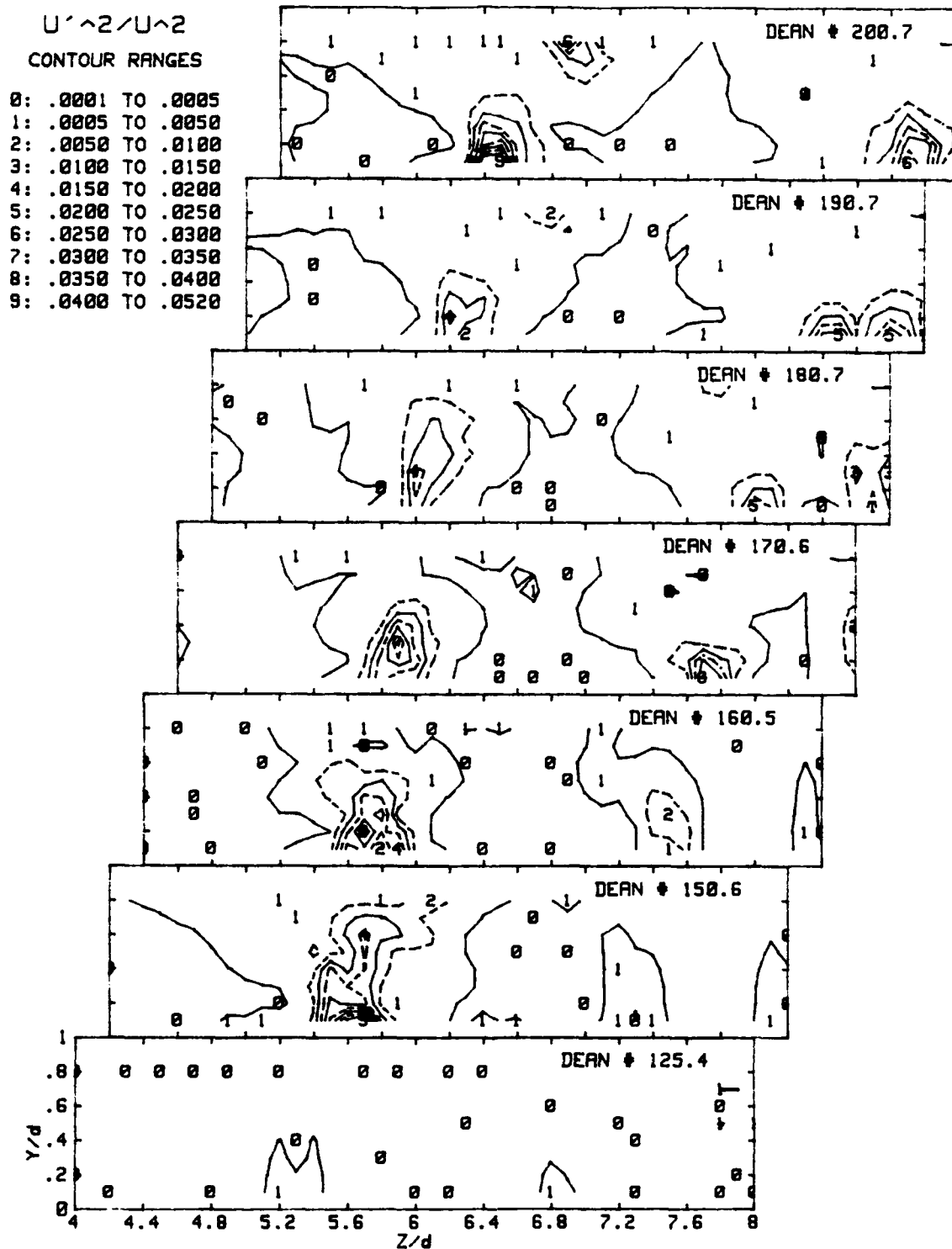


Figure 28. Longitudinal Reynolds Normal Stress Normalized by the Local Mean Velocity Squared,  $De=125.4$  to  $De=200.7$

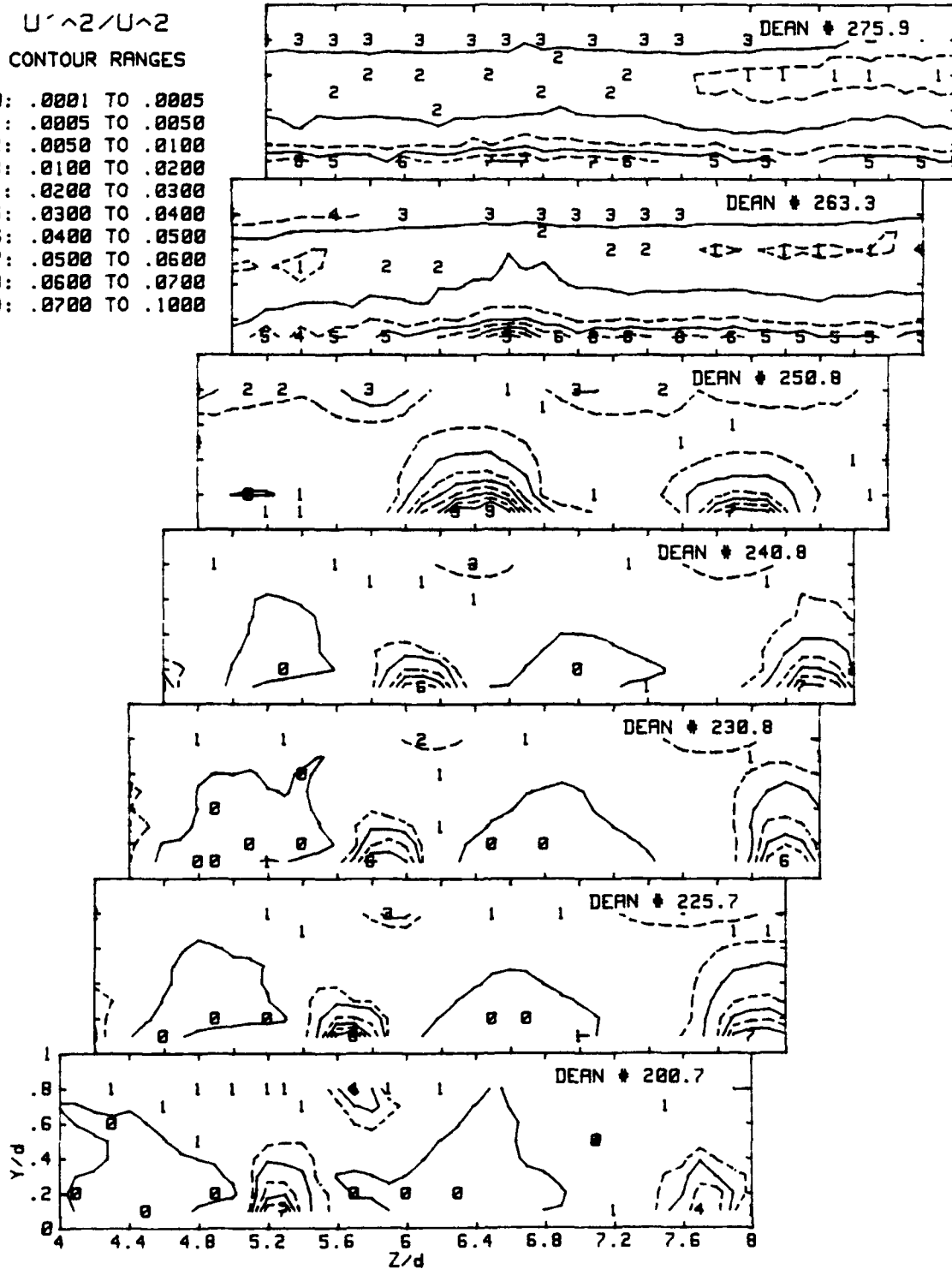


Figure 29. Longitudinal Reynolds Normal Stress Normalized by the Local Mean Velocity Squared,  $De=200.7$  to  $De=275.9$

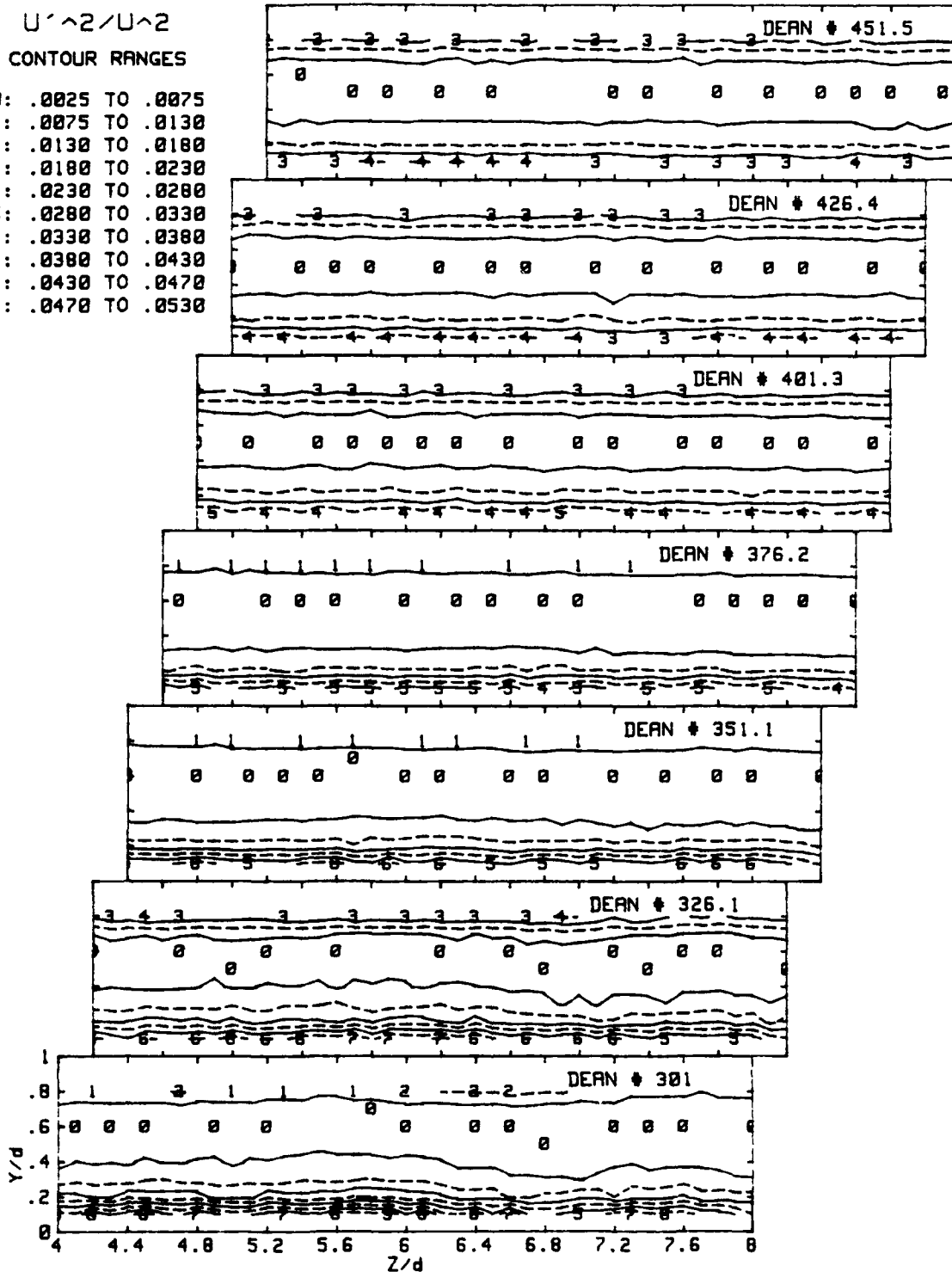


Figure 30. Longitudinal Reynolds Normal Stress Normalized by the Local Mean Velocity Squared,  $De=301.0$  to  $De=451.5$

$$U'^2/U_{bulk}^2$$

CONTOUR RANGES

- 0: .0000 TO .0001
- 1: .0001 TO .0002
- 2: .0002 TO .0003
- 3: .0003 TO .0003
- 4: .0003 TO .0004
- 5: .0004 TO .0005
- 6: .0005 TO .0005
- 7: .0005 TO .0006
- 8: .0006 TO .0007
- 9: .0007 TO .0007

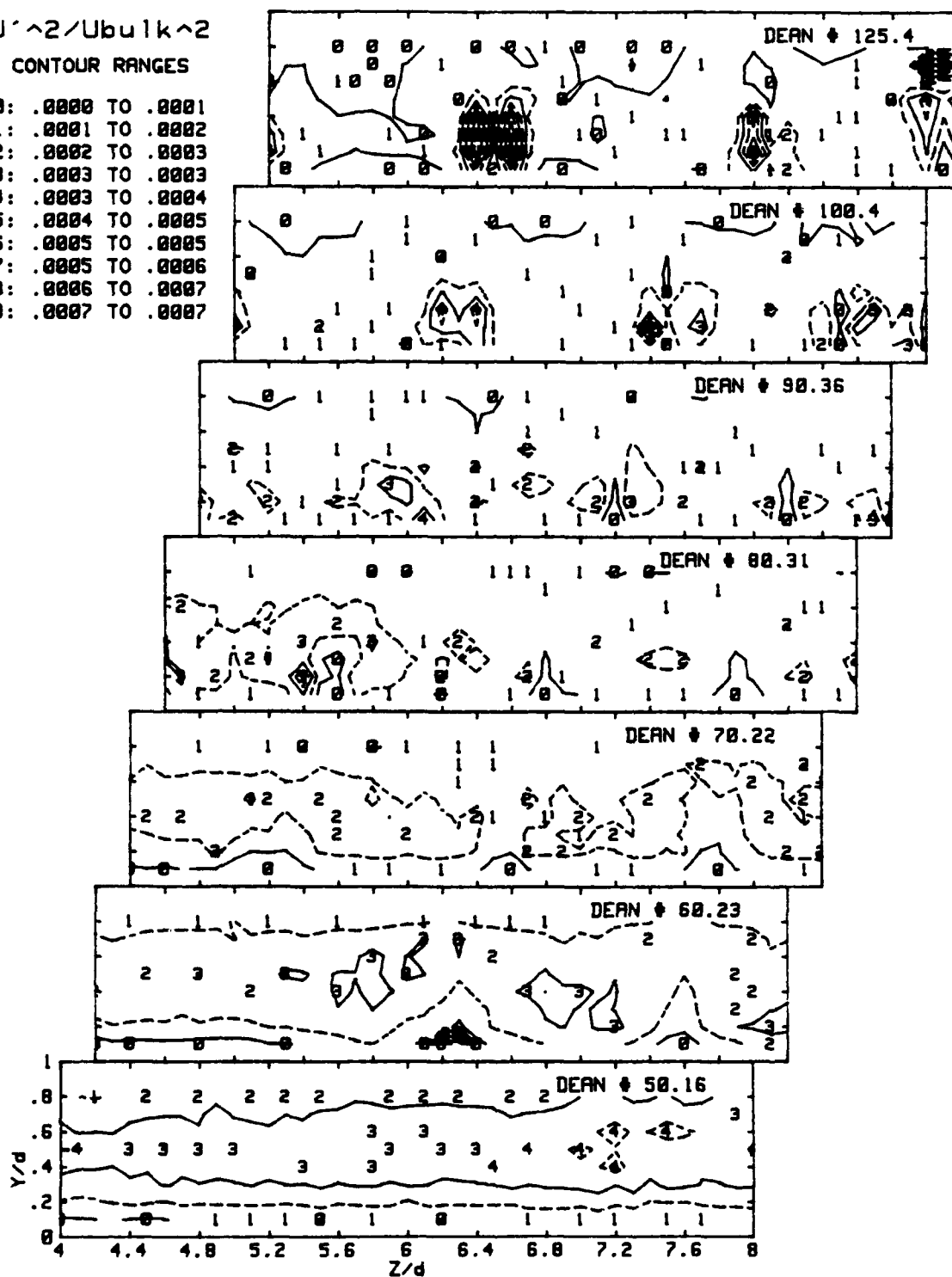


Figure 31. Longitudinal Reynolds Normal Stress Normalized by the Bulk Velocity Squared,  $De=50.2$  to  $De=125.4$

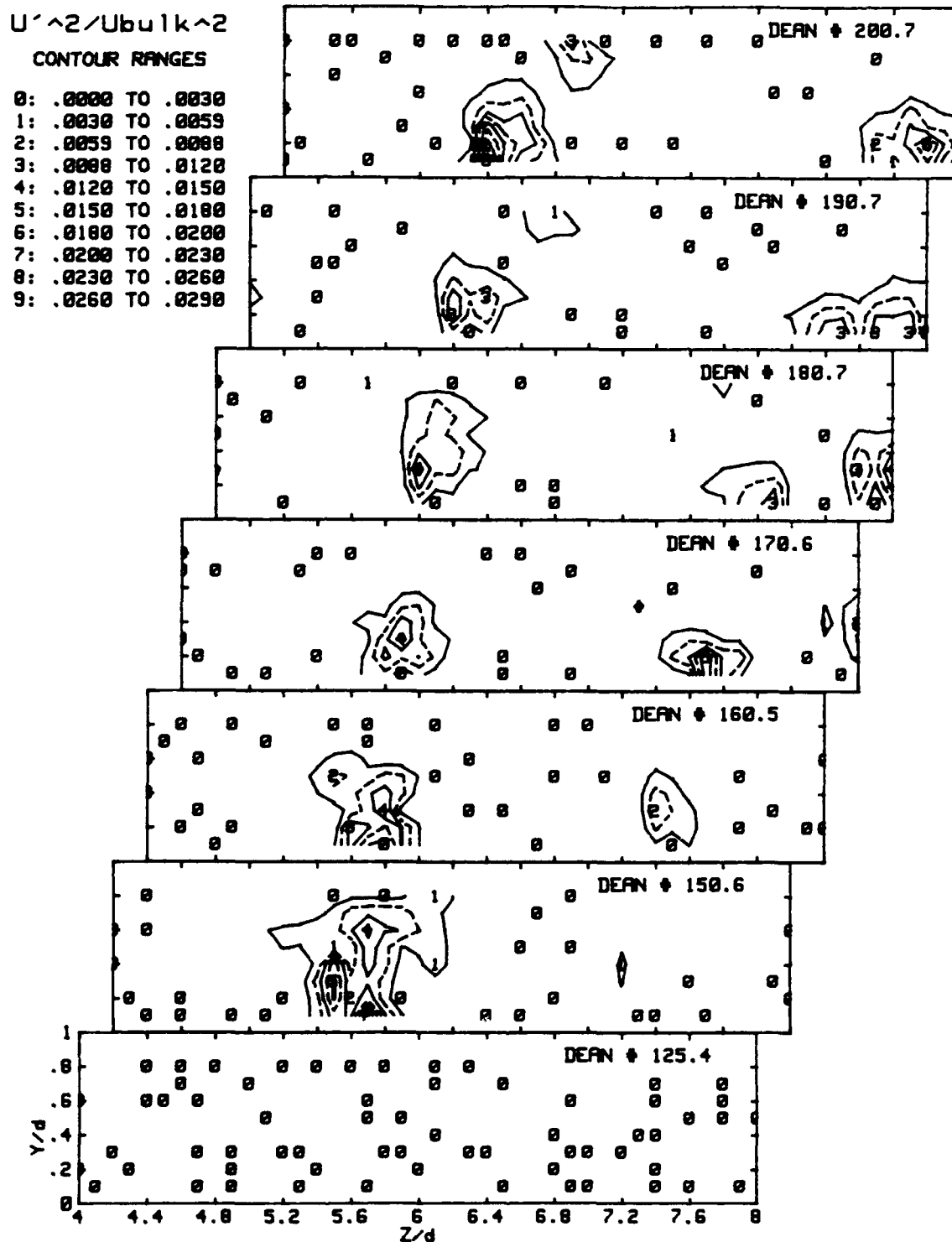


Figure 32. Longitudinal Reynolds Normal Stress Normalized by the Bulk Velocity Squared,  $De=125.4$  to  $De=200.7$



$$U'^2/U_b^2 k^2$$

CONTOUR RANGES

- 0: .0001 TO .0051
- 1: .0051 TO .0100
- 2: .0100 TO .0150
- 3: .0150 TO .0200
- 4: .0200 TO .0250
- 5: .0250 TO .0300
- 6: .0300 TO .0350
- 7: .0350 TO .0400
- 8: .0400 TO .0450
- 9: .0450 TO .0500

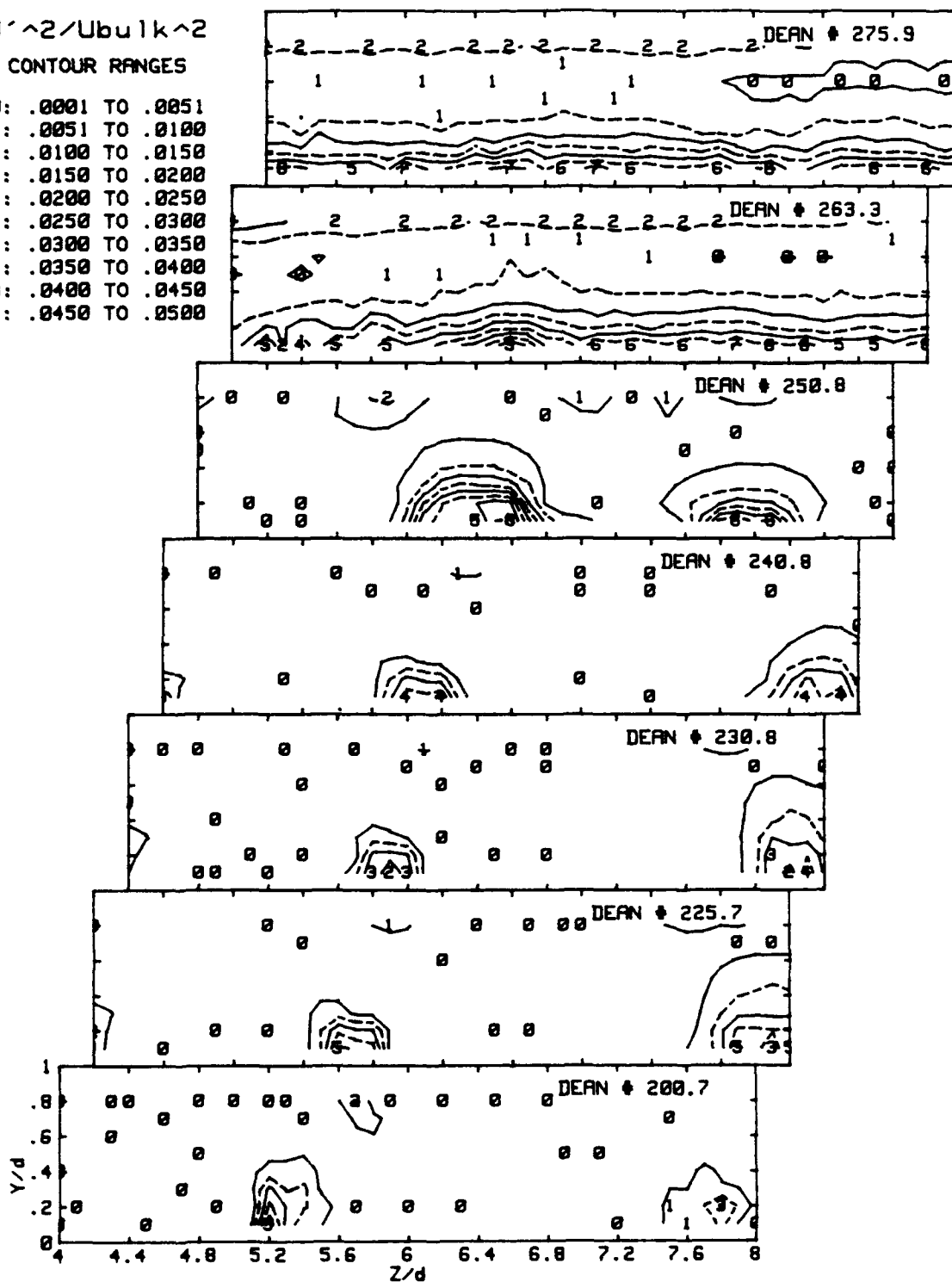


Figure 33. Longitudinal Reynolds Normal Stress Normalized by the Bulk Velocity Squared,  $De=200.7$  to  $De=275.9$

$$U'^2/U_{bulk}^2$$

CONTOUR RANGES

- 0: .0035 TO .0072
- 1: .0072 TO .0110
- 2: .0110 TO .0150
- 3: .0150 TO .0180
- 4: .0180 TO .0220
- 5: .0220 TO .0260
- 6: .0260 TO .0290
- 7: .0290 TO .0330
- 8: .0330 TO .0370
- 9: .0370 TO .0400

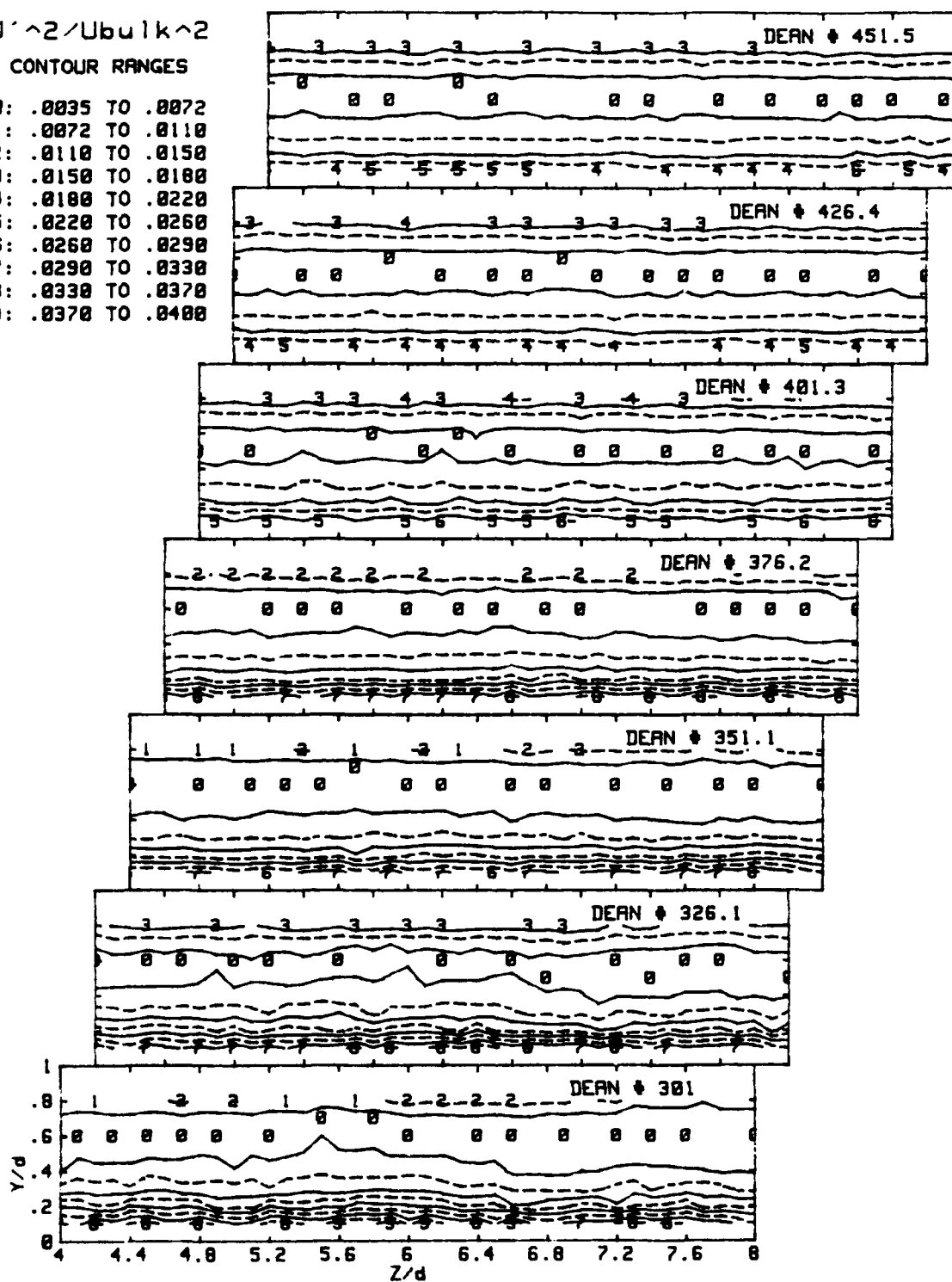
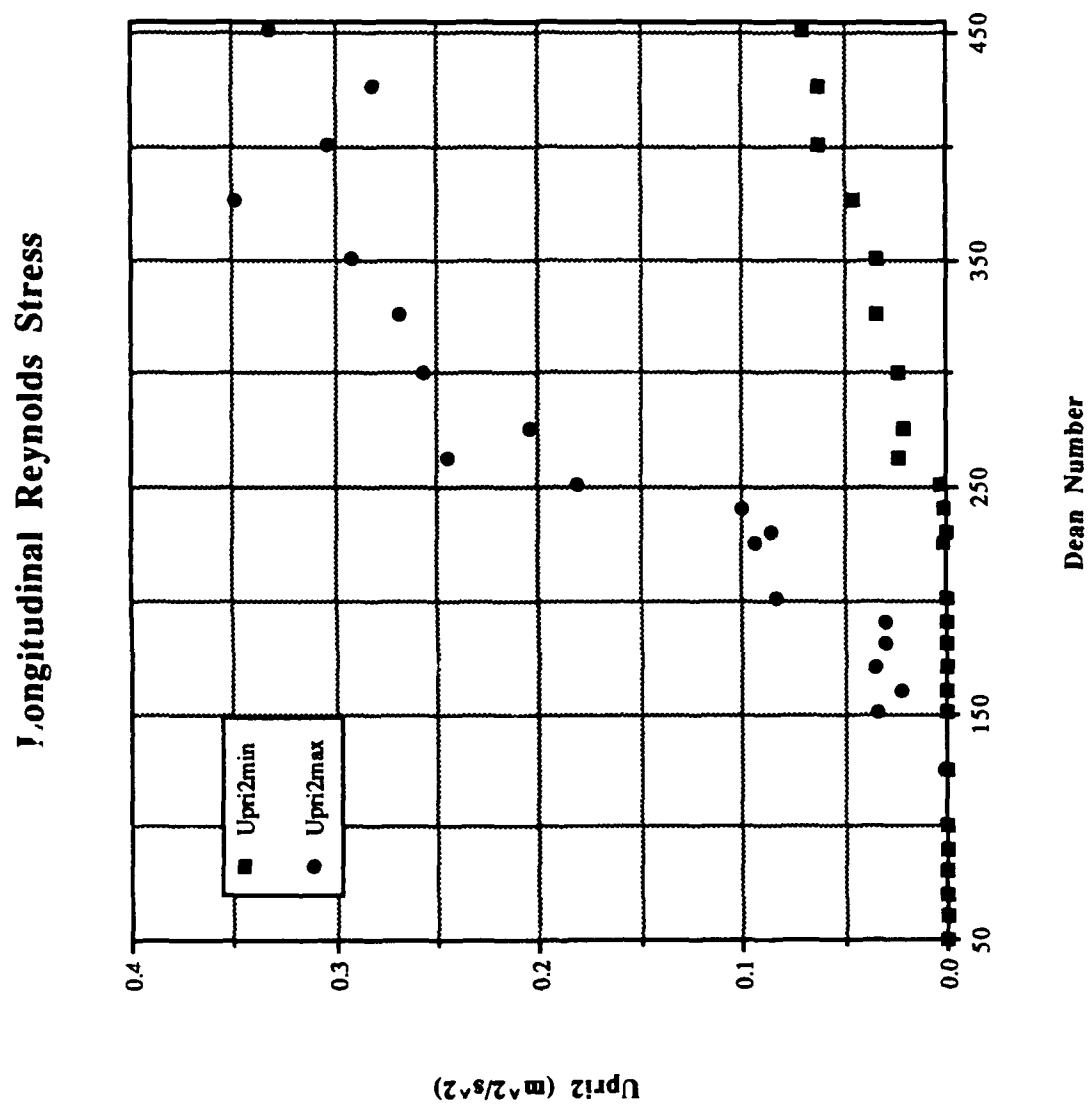


Figure 34. Longitudinal Reynolds Normal Stress Normalized by the Bulk Velocity Squared,  $De=301.0$  to  $De=451.5$



**Figure 35. Maximum and Minimum Longitudinal Reynolds Stress,  
De=50.2 to 451.5**

# Longitudinal Reynolds Stress

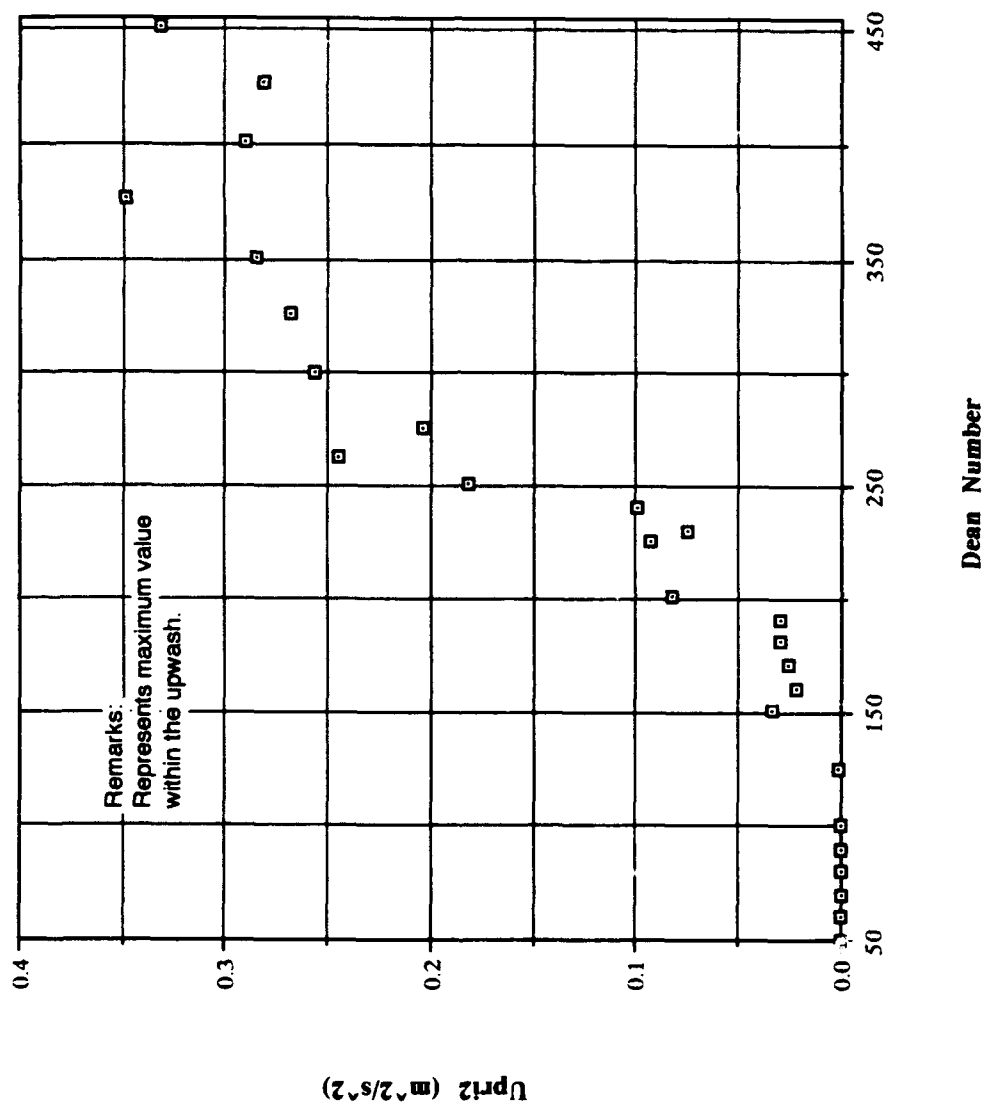


Figure 36. Maximum Value of Longitudinal Reynolds Normal Stress Within Left Most Upwash Region

# Longitudinal Reynolds Stress

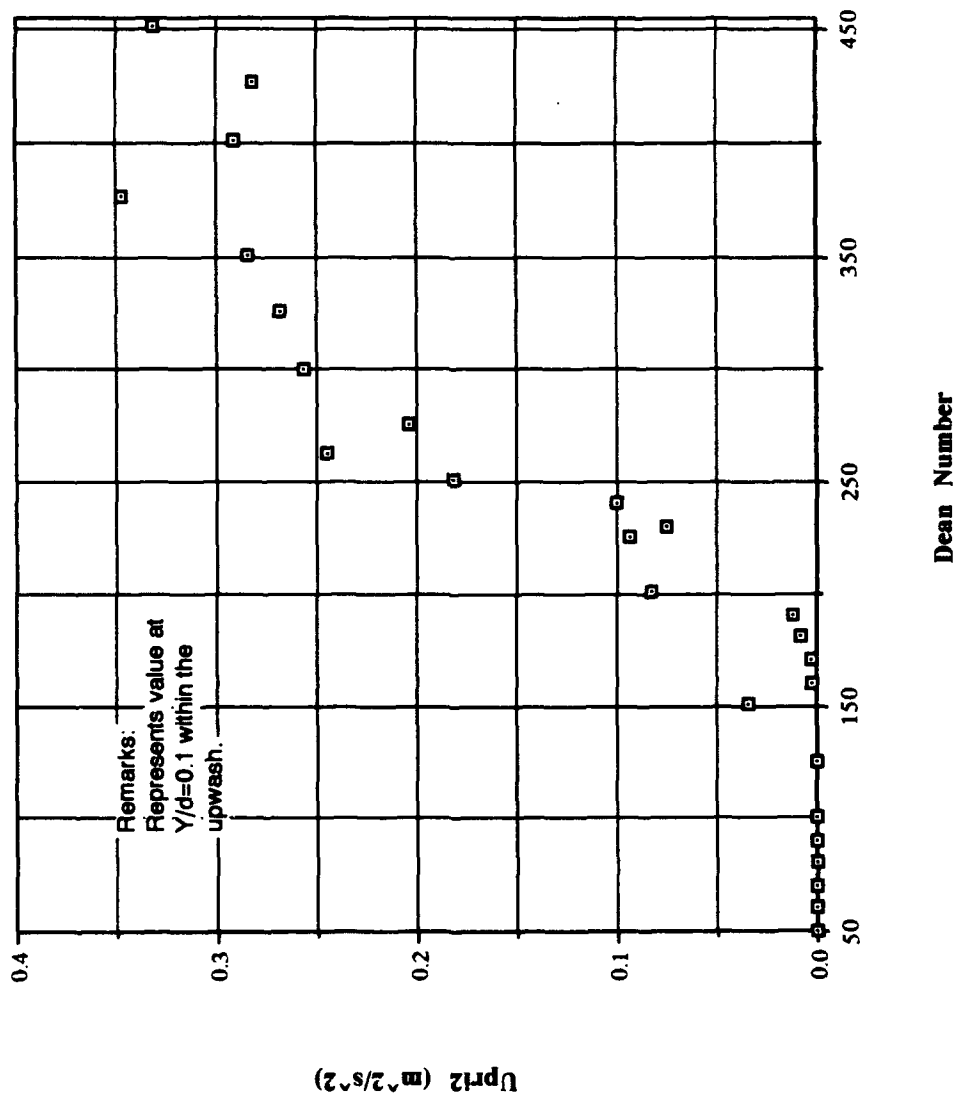


Figure 37. Longitudinal Reynolds Normal Stress for  $Y/d=0.1$  Within Left Most Upwash Region

# Longitudinal Reynolds Stress

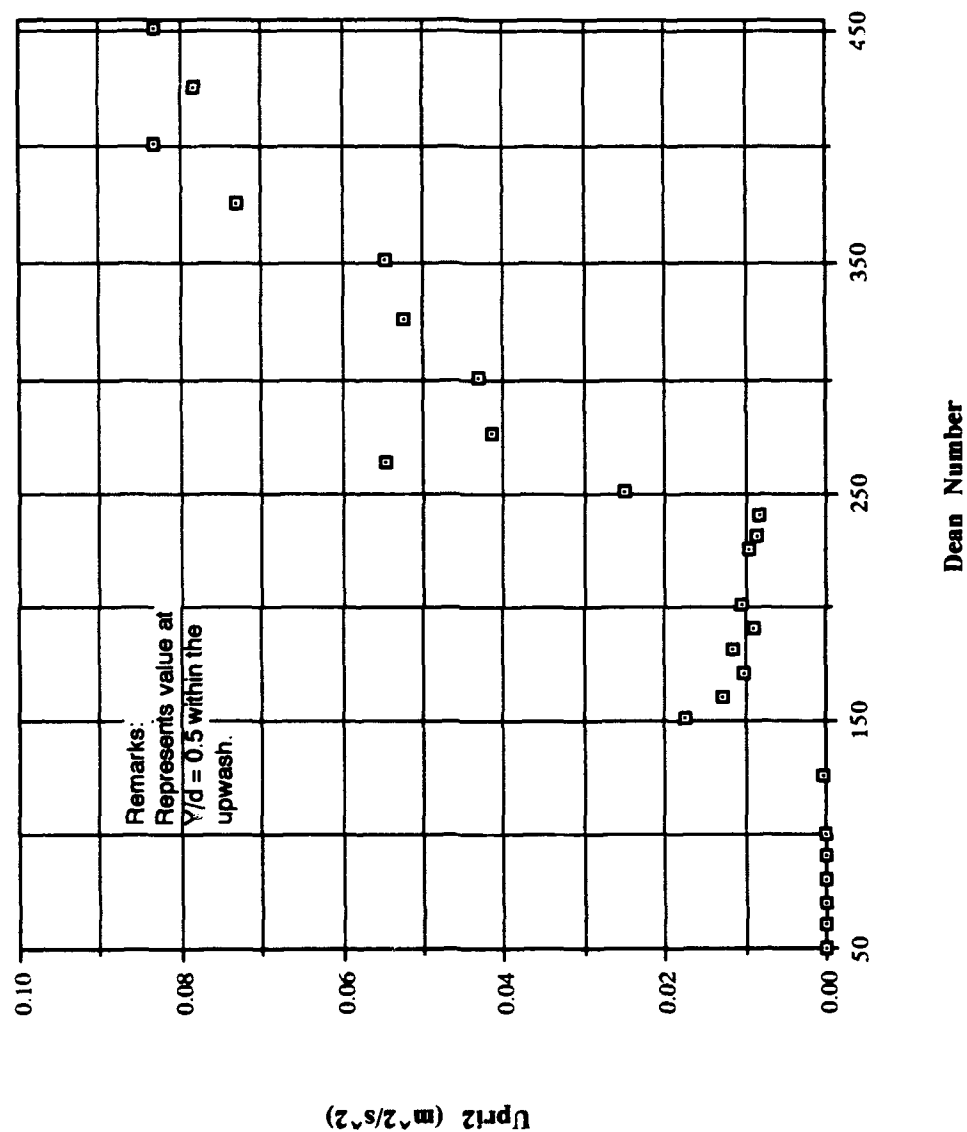


Figure 38. Longitudinal Reynolds Normal Stress for  $Y/d=0.5$  Within Left Most Upwash Region

# Longitudinal Reynolds Stress

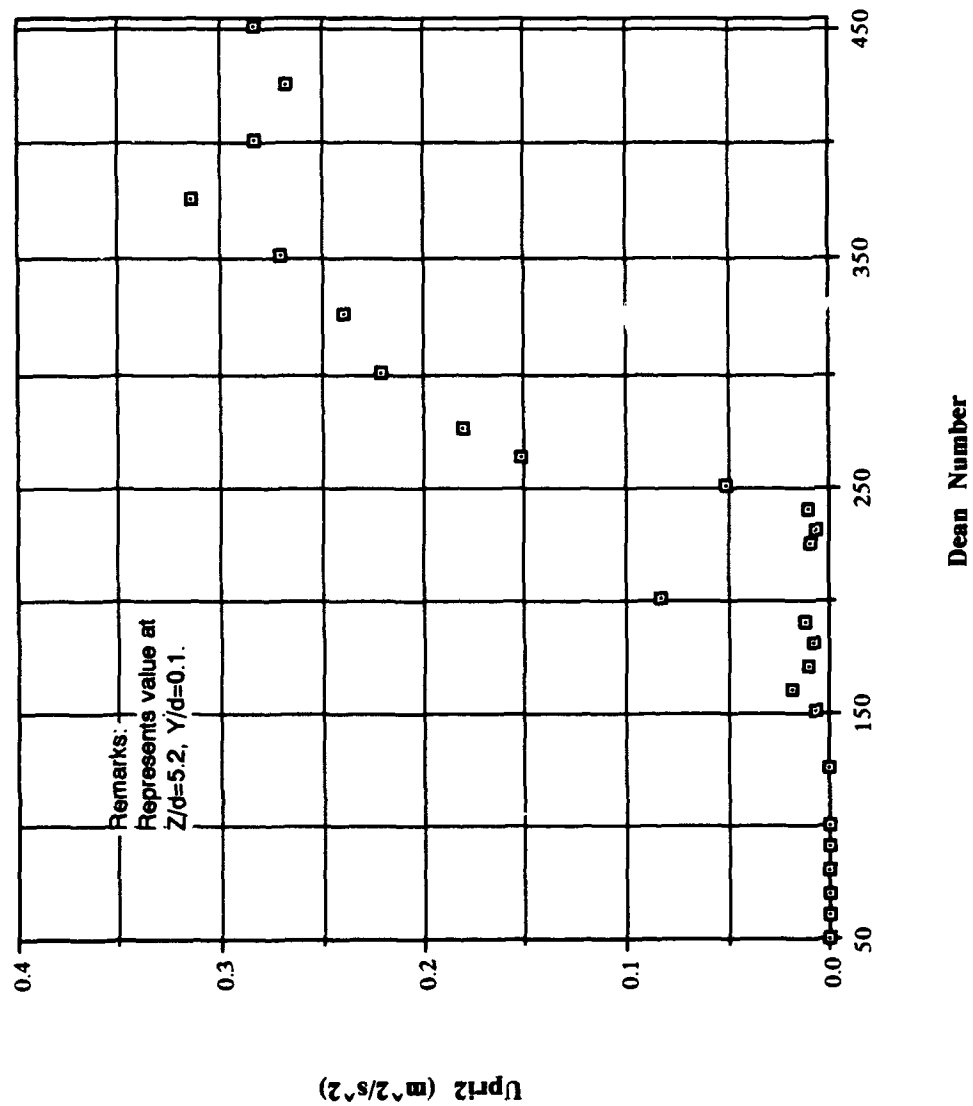


Figure 39. Longitudinal Reynolds Normal Stress for  $Z/d=5.2, Y/d=0.1$   
Within Left Most Upwash Region

# Longitudinal Reynolds Stress

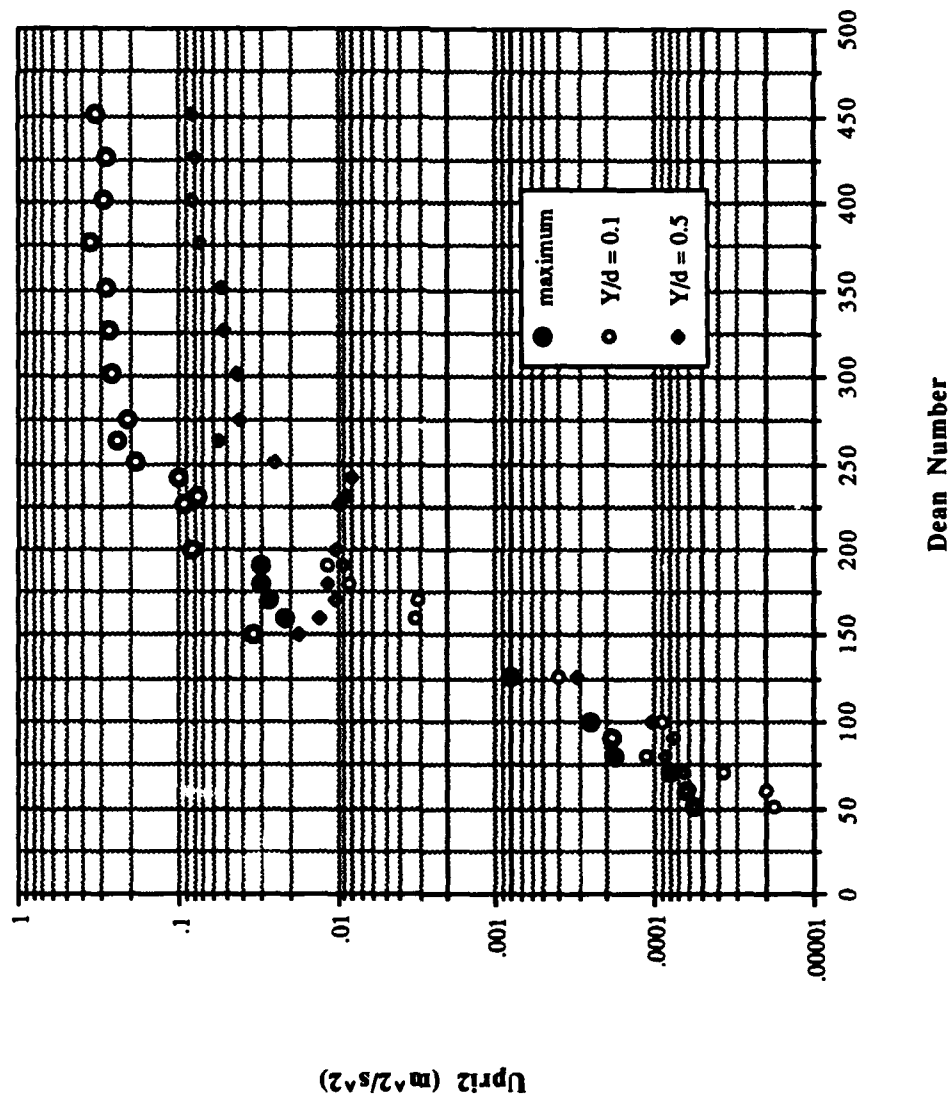


Figure 40. Longitudinal Reynolds Normal Stress Within Left Most Upwash Region,  $De=50.2$  to  $De=451.5$ . Data are presented for three positions: maximum value,  $Y/d=0.1$ , and  $Y/d=0.5$



# Longitudinal Reynolds Stress

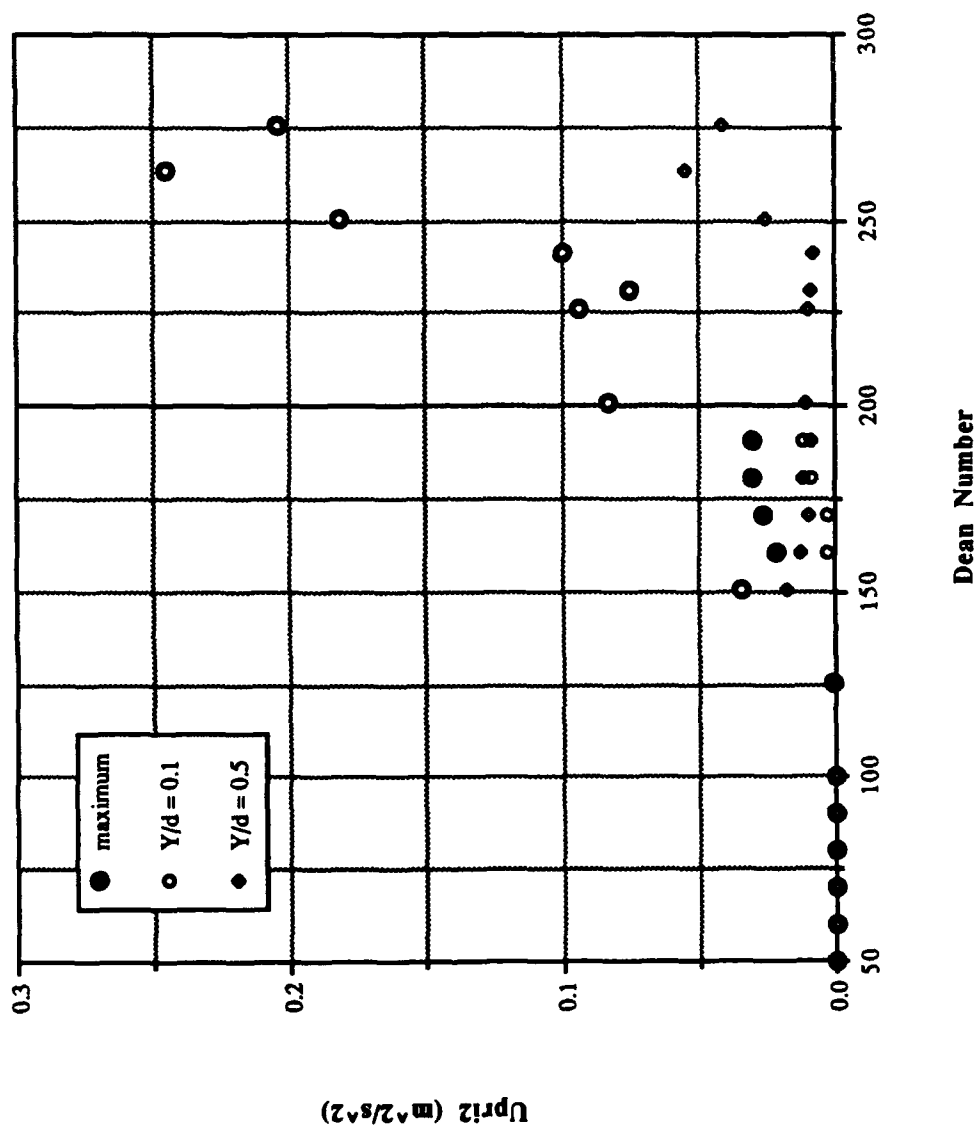
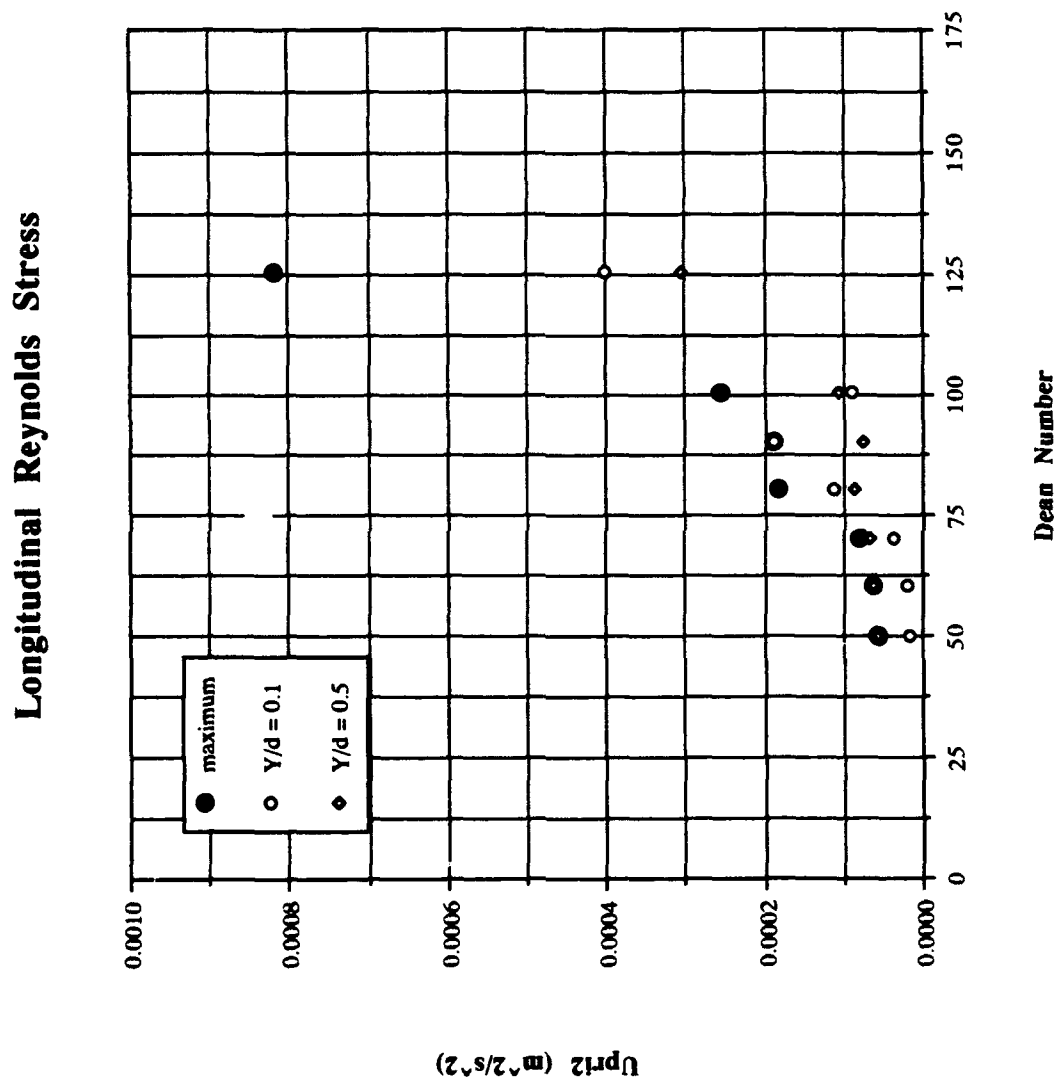


Figure 41. Longitudinal Reynolds Normal Stress Within Left Most Upwash Region,  $De=50.2$  to  $De=275.9$ . Data are presented for three positions: maximum value,  $Y/d=0.1$ , and  $Y/d=0.5$



**Figure 42. Longitudinal Reynolds Normal Stress Within Left Most Upwash Region,  $De=50.2$  to  $De=125.4$ . Data are presented for three positions: maximum value,  $Y/d=0.1$ , and  $Y/d=0.5$**

# Streamwise Mean Velocity Near Wall Profile

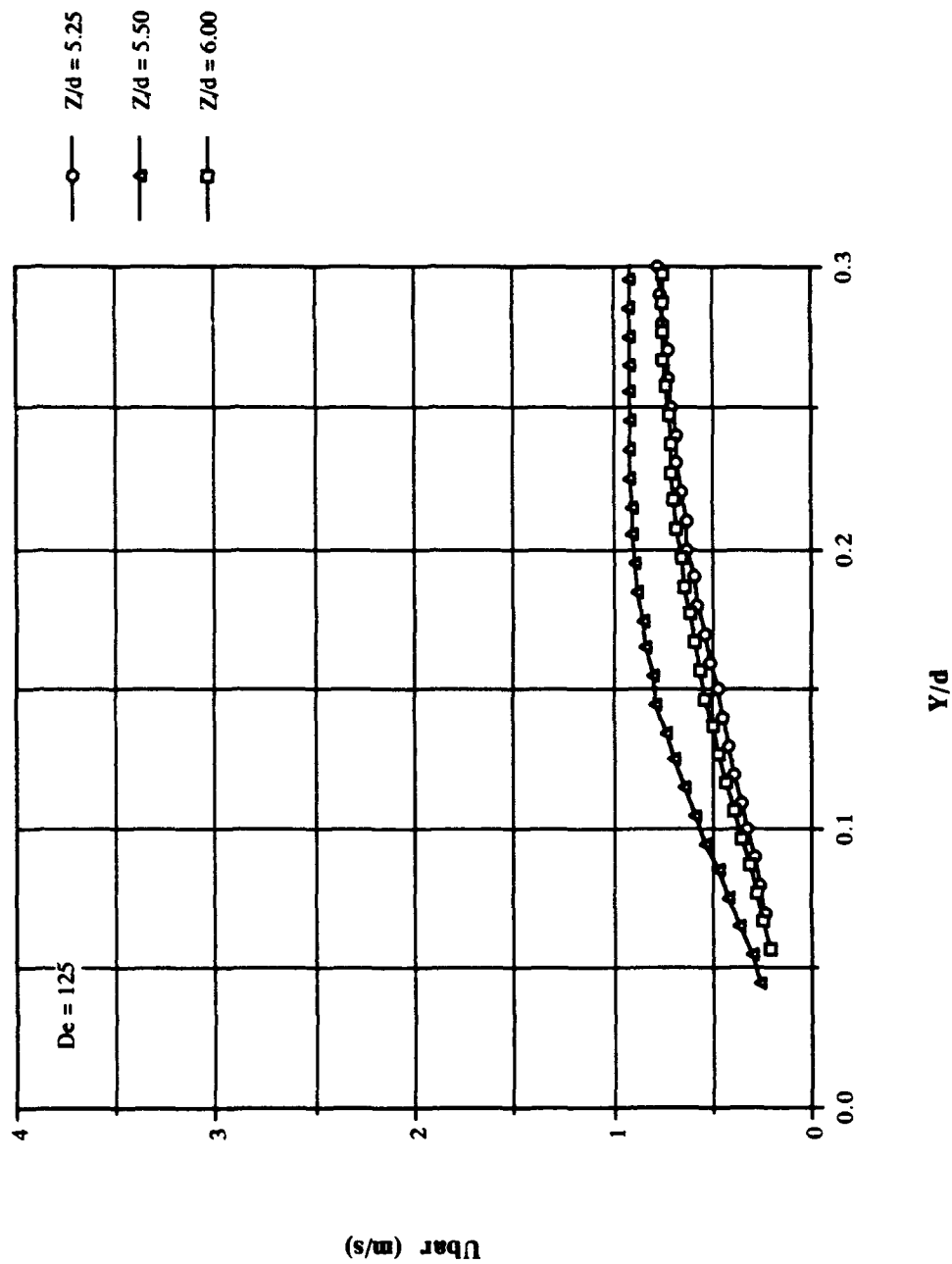


Figure 43. Streamwise Mean Velocity Profiles,  $De=125$

# Streamwise Mean Velocity Near Wall Results

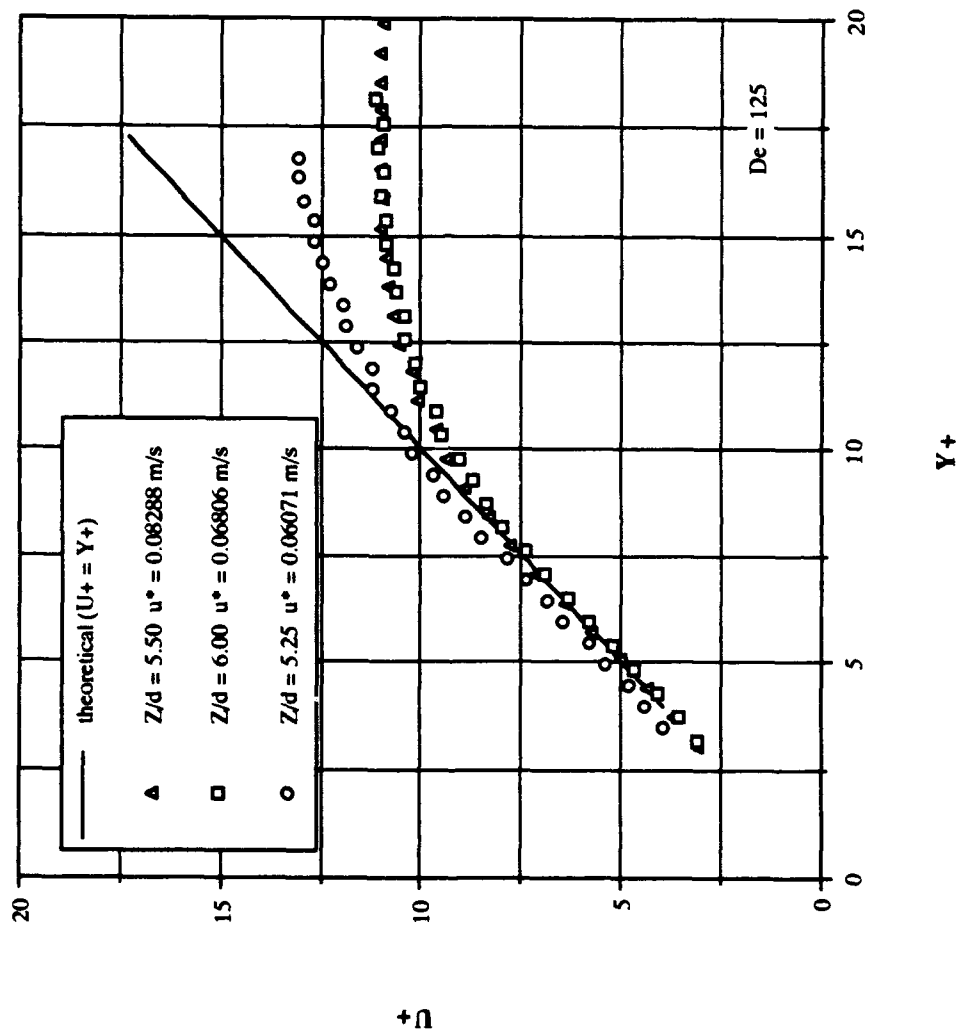


Figure 44. Mean Velocity Profiles in Wall Coordinates,  $De=125$

# Streamwise Mean Velocity Near Wall Profile

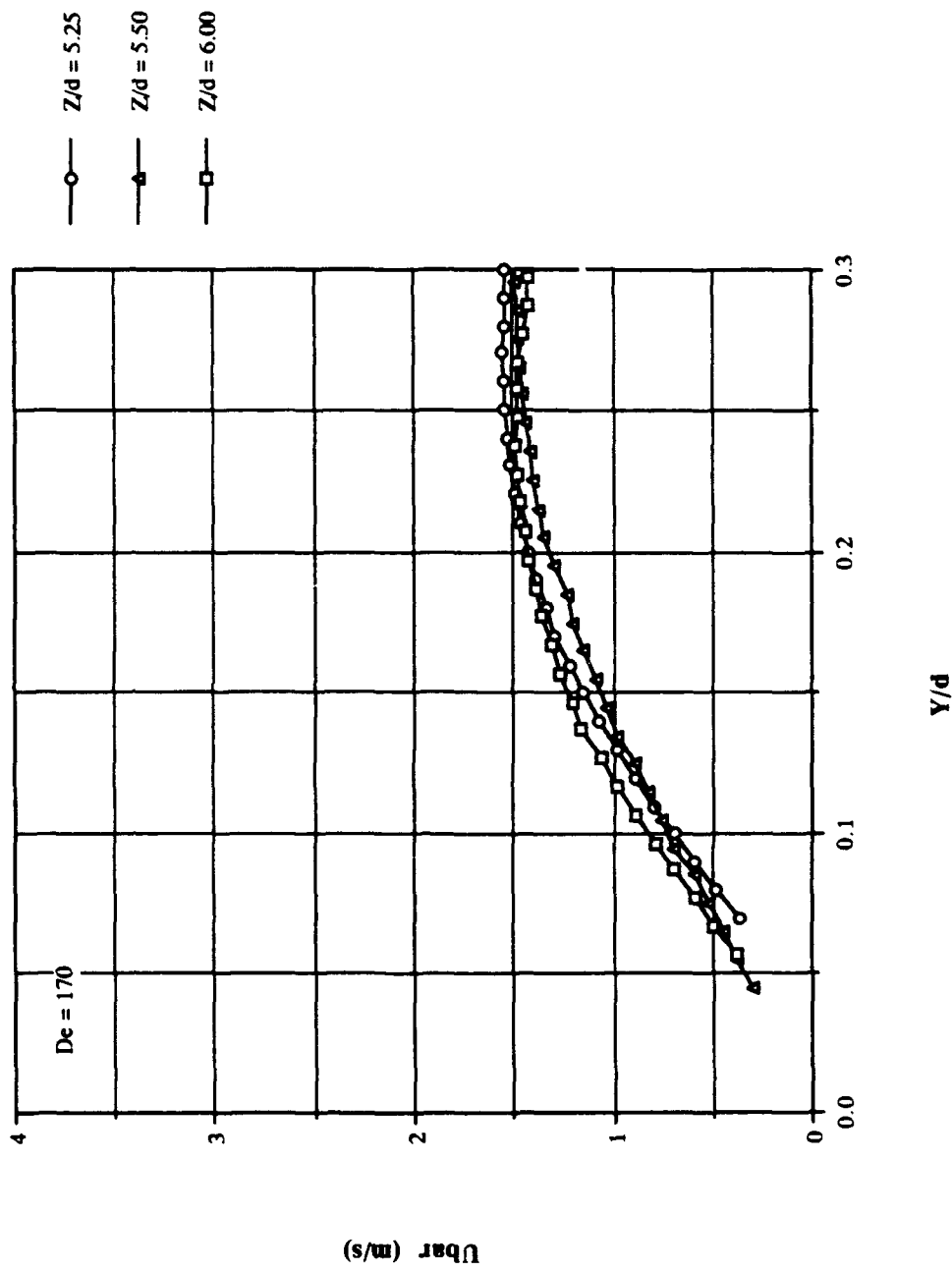


Figure 45. Streamwise Mean Velocity Profiles,  $De=170$

# Streamwise Mean Velocity Near Wall Profile

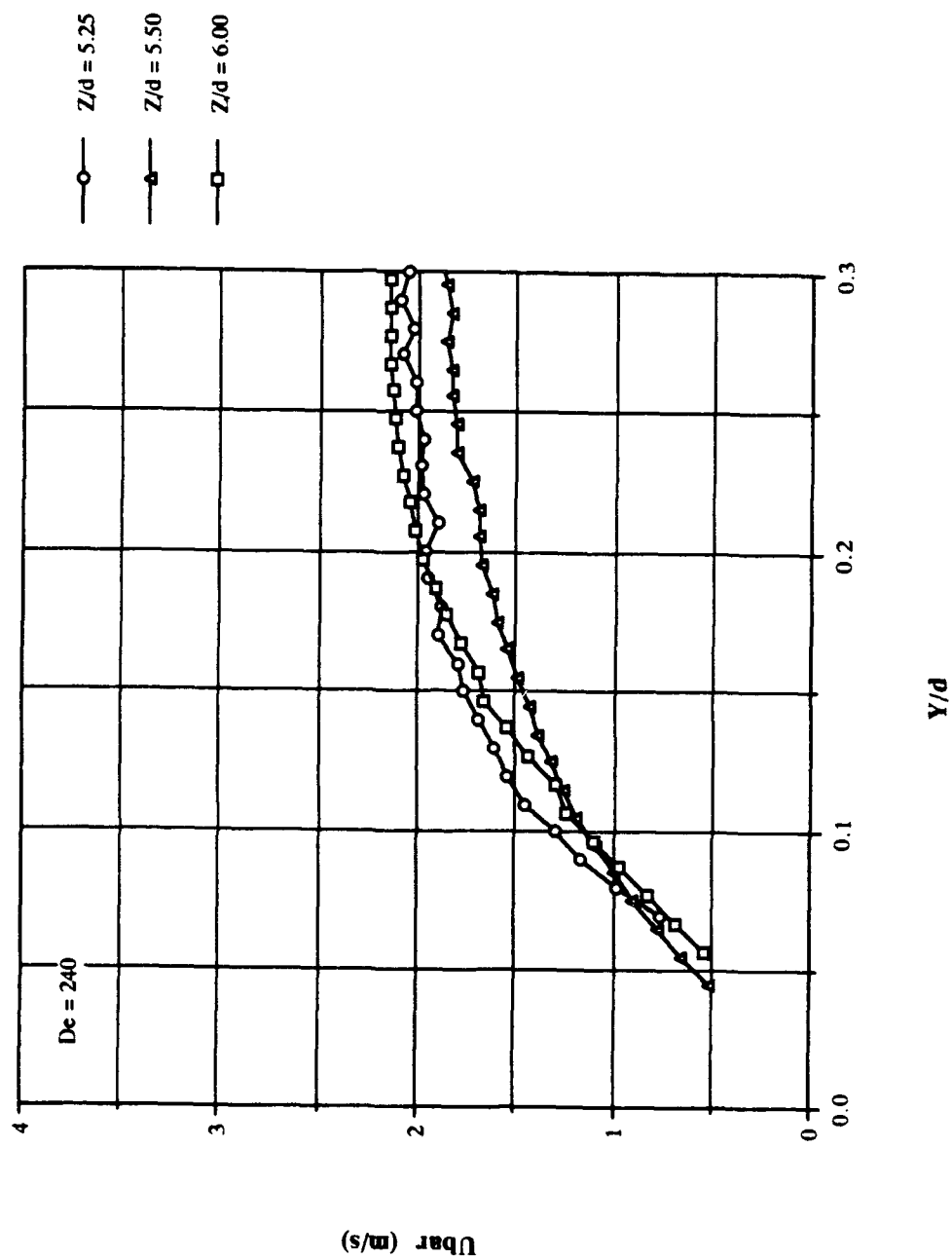


Figure 46. Streamwise Mean Velocity Profiles,  $De=240$

# Streamwise Mean Velocity Near Wall Profile

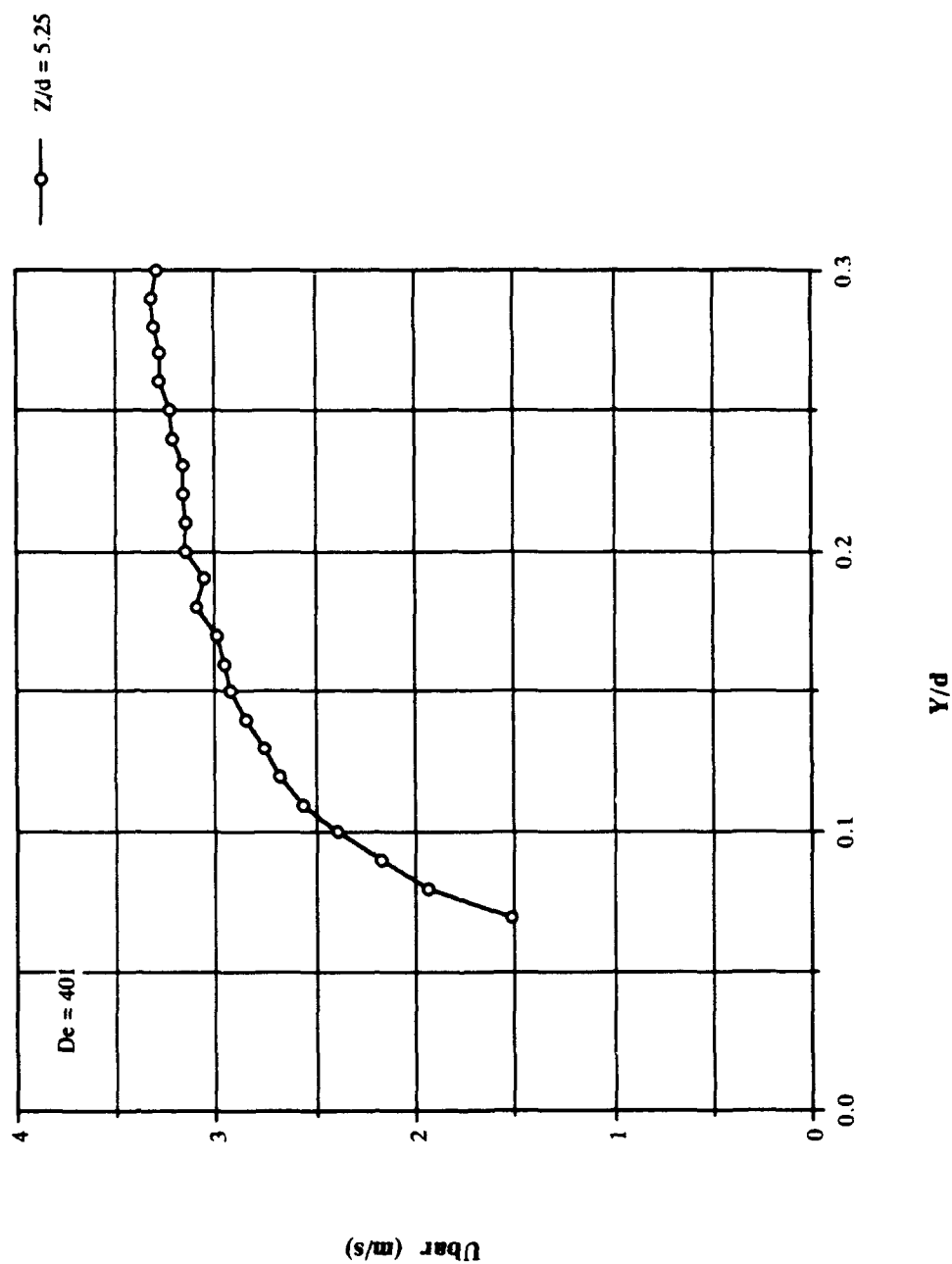


Figure 47. Streamwise Mean Velocity Profile,  $De=401$

# Streamwise Mean Velocity Near Wall Results

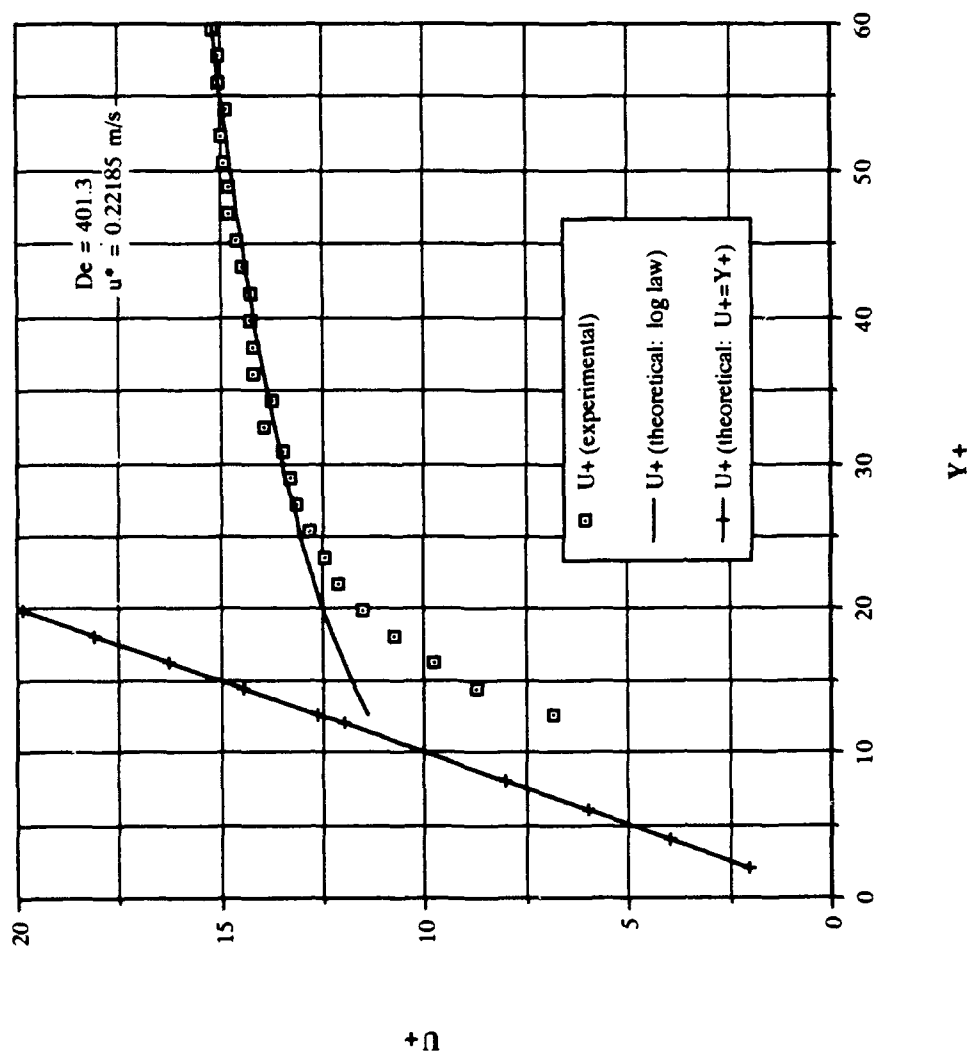


Figure 48. Mean Velocity Profile in Wall Coordinates, De=401



# Streamwise Mean Velocity Near Wall Results

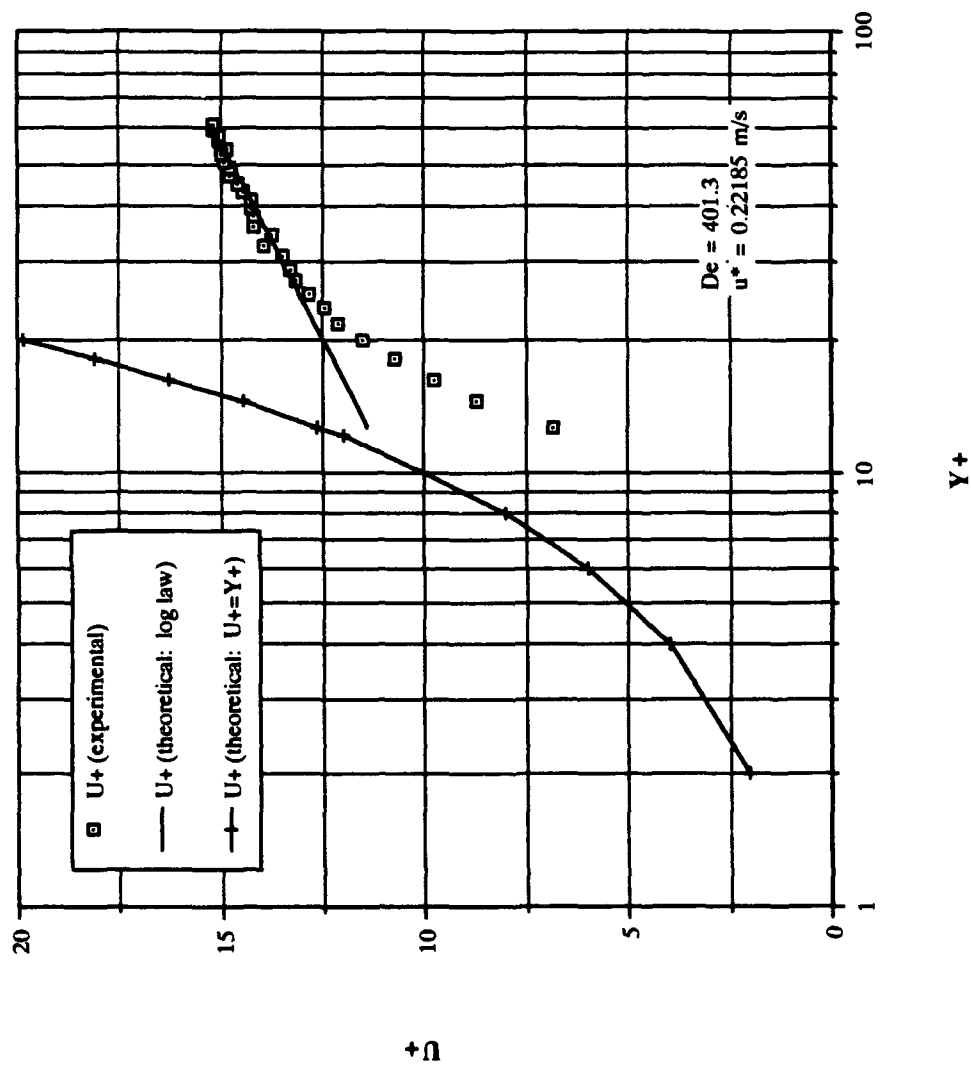


Figure 49. Semi-log Plot of Streamwise Mean Velocity Profile in Wall Coordinates, De=401

# Longitudinal Reynolds Stress Near Wall Profile

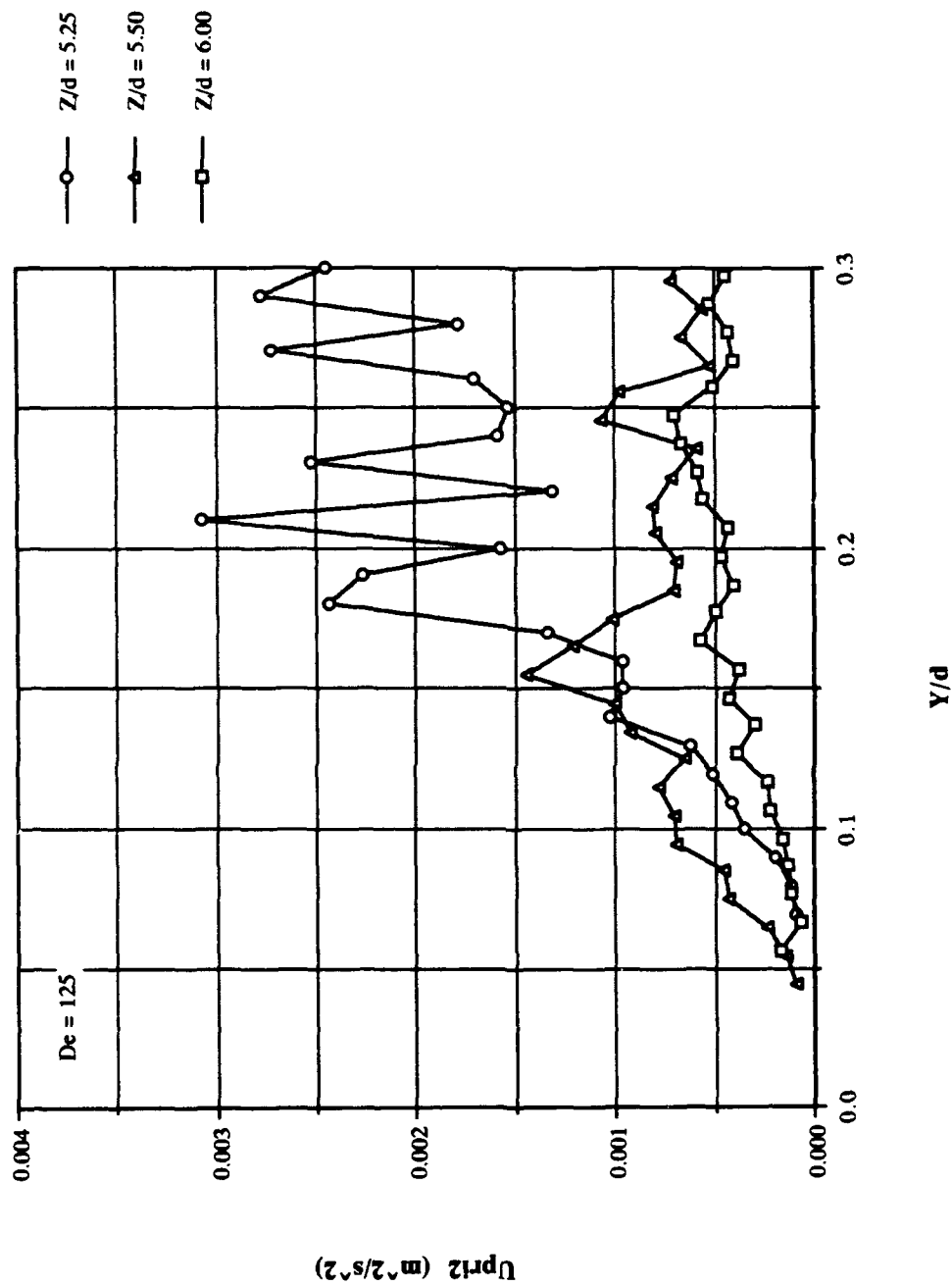


Figure 50. Longitudinal Reynolds Normal Stress Profiles, De=125

# Longitudinal Reynolds Stress Near Wall Profile

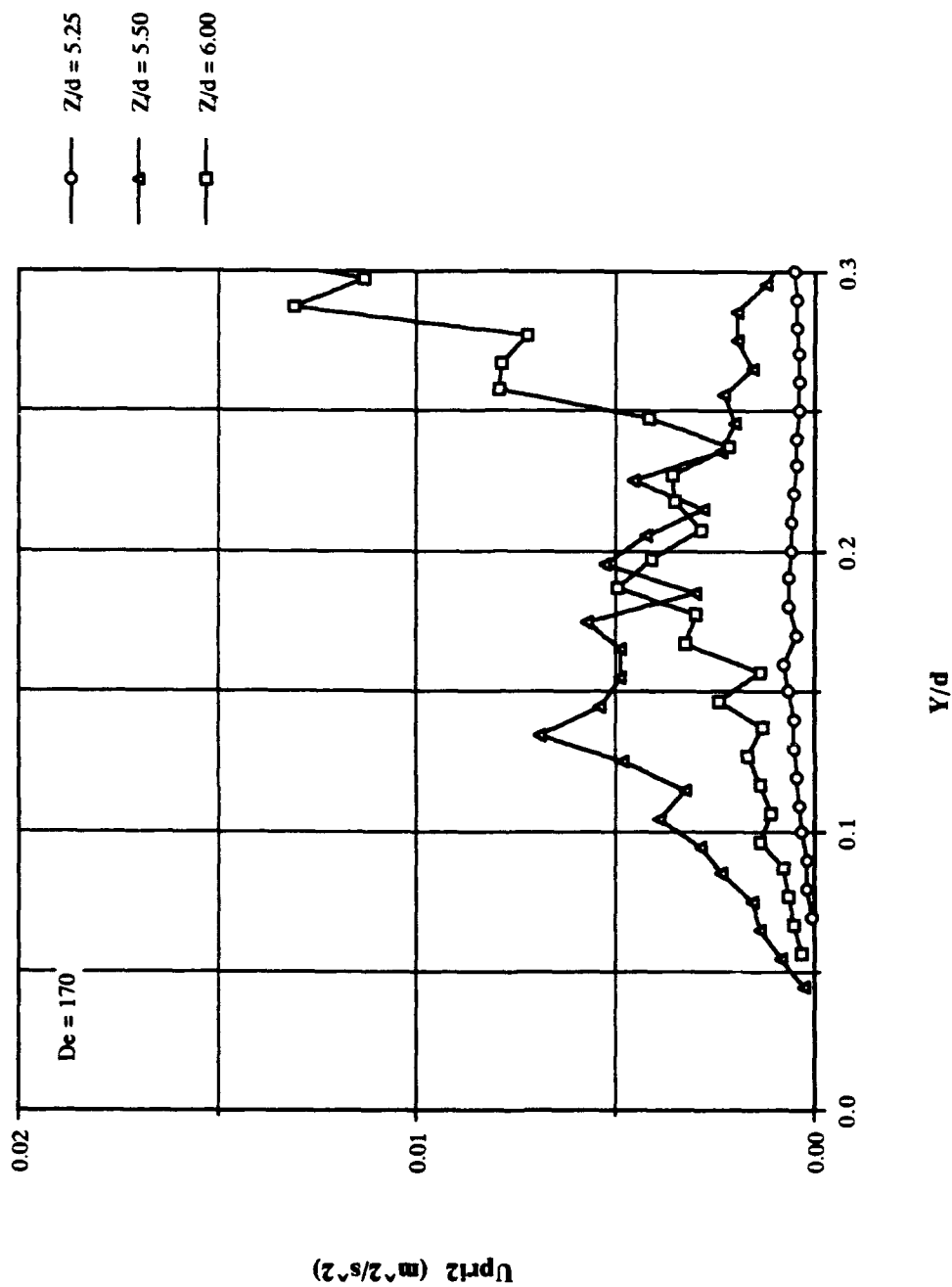


Figure 51. Longitudinal Reynolds Normal Stress Profiles, De=170

# Longitudinal Reynolds Stress Near Wall Profile

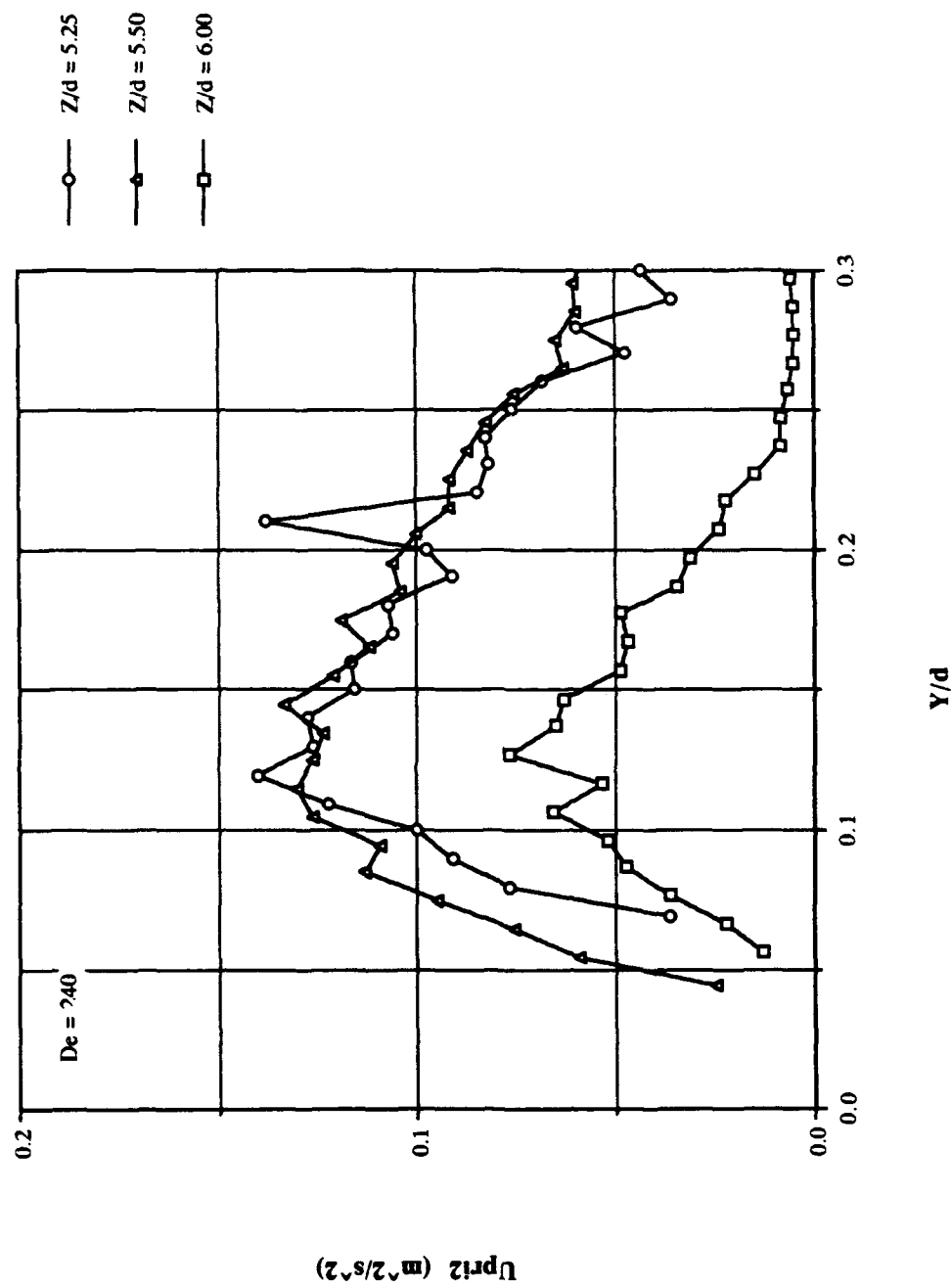


Figure 52. Longitudinal Reynolds Normal Stress Profiles, De=240

# Longitudinal Reynolds Stress Near Wall Profile

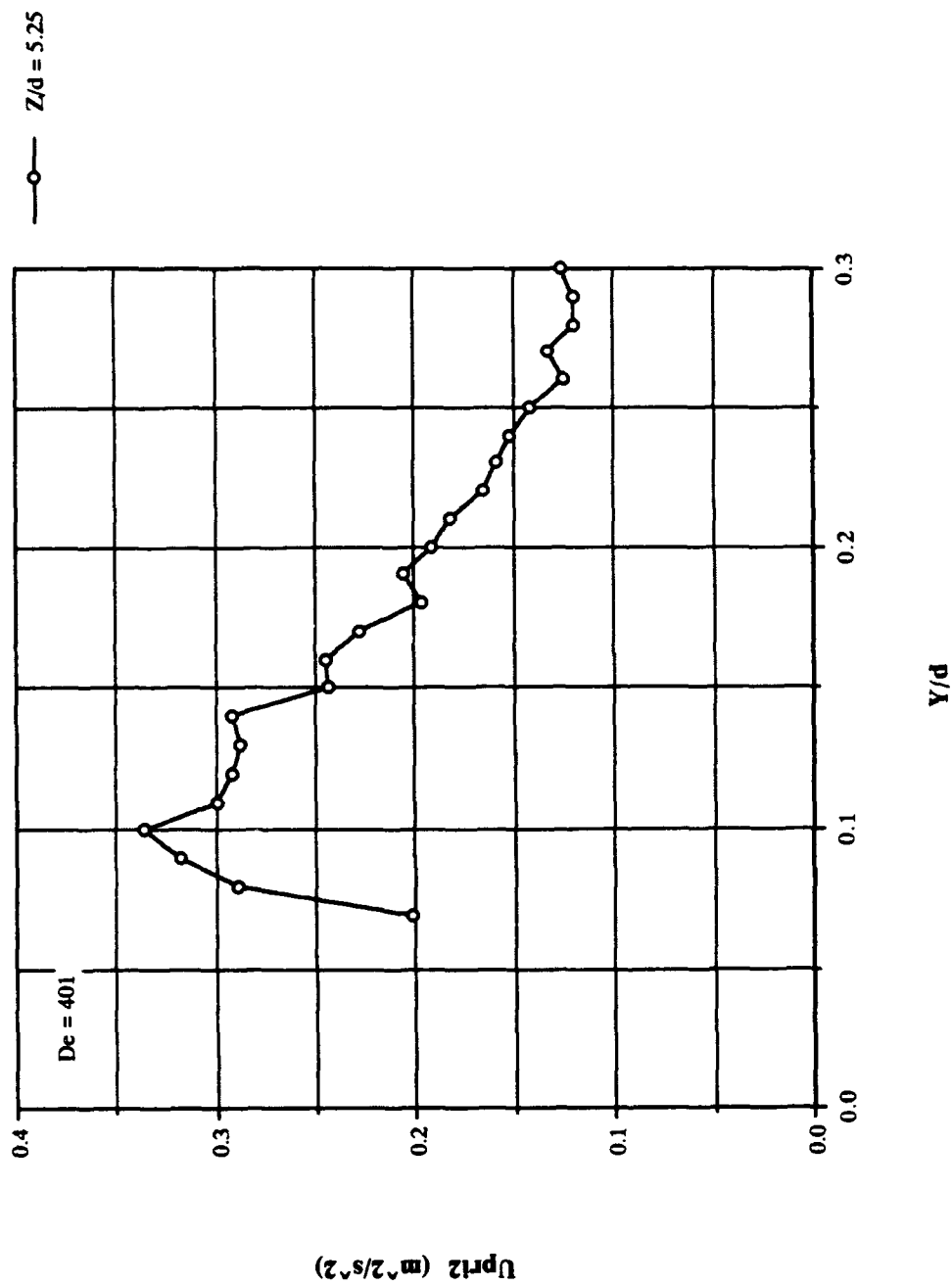


Figure 53. Longitudinal Reynolds Normal Stress Profiles, De=401

# Normalized Longitudinal Reynolds Stress Near Wall Profile

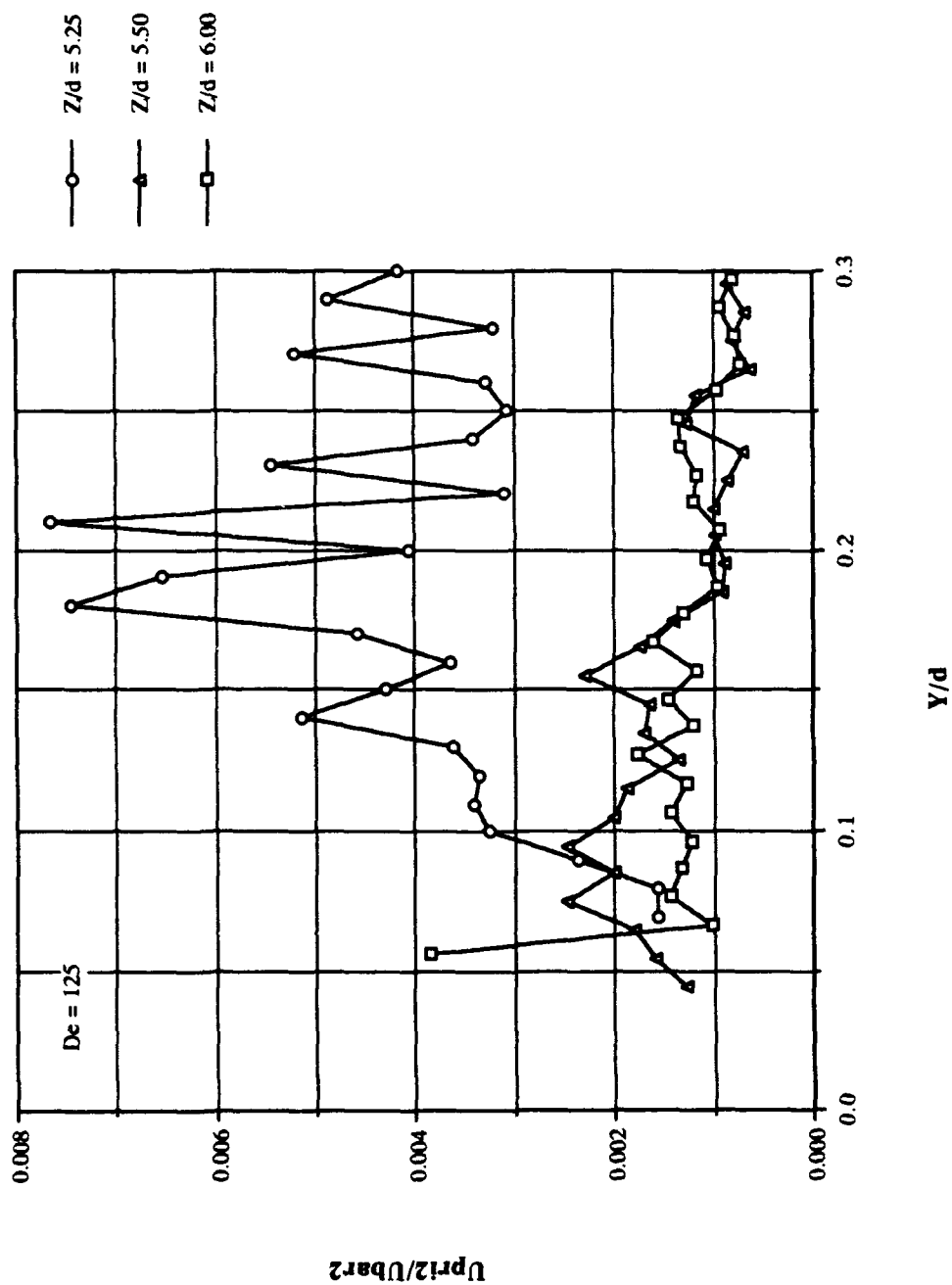


Figure 54. Normalized Longitudinal Reynolds Stress Profiles, De=125

# Normalized Longitudinal Reynolds Stress Near Wall Profile

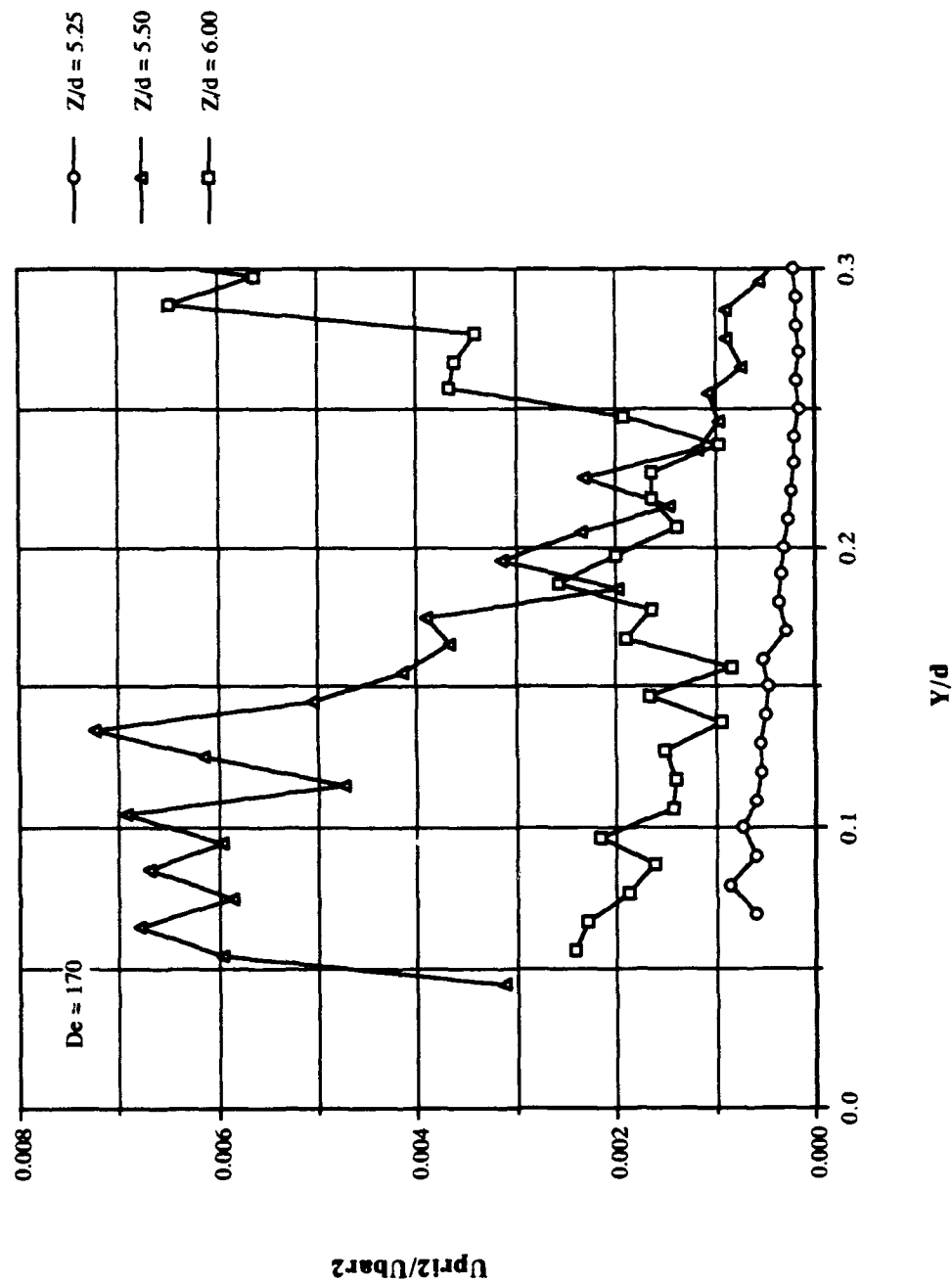


Figure 55. Normalized Longitudinal Reynolds Stress Profiles,  $De=170$

# Normalized Longitudinal Reynolds Stress Near Wall Profile

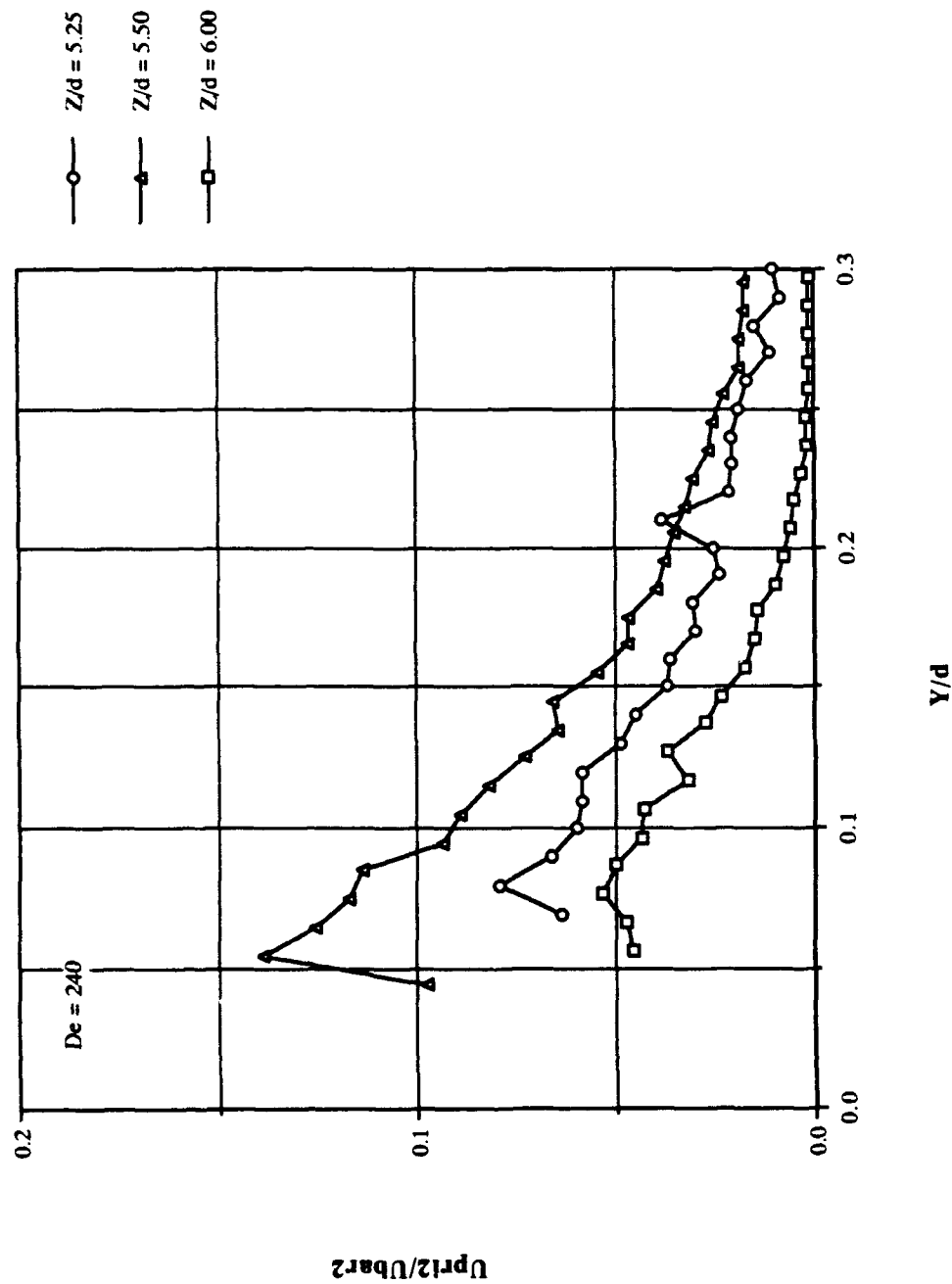


Figure 56. Normalized Longitudinal Reynolds Stress Profiles, De=240



# Normalized Longitudinal Reynolds Stress Near Wall Profile

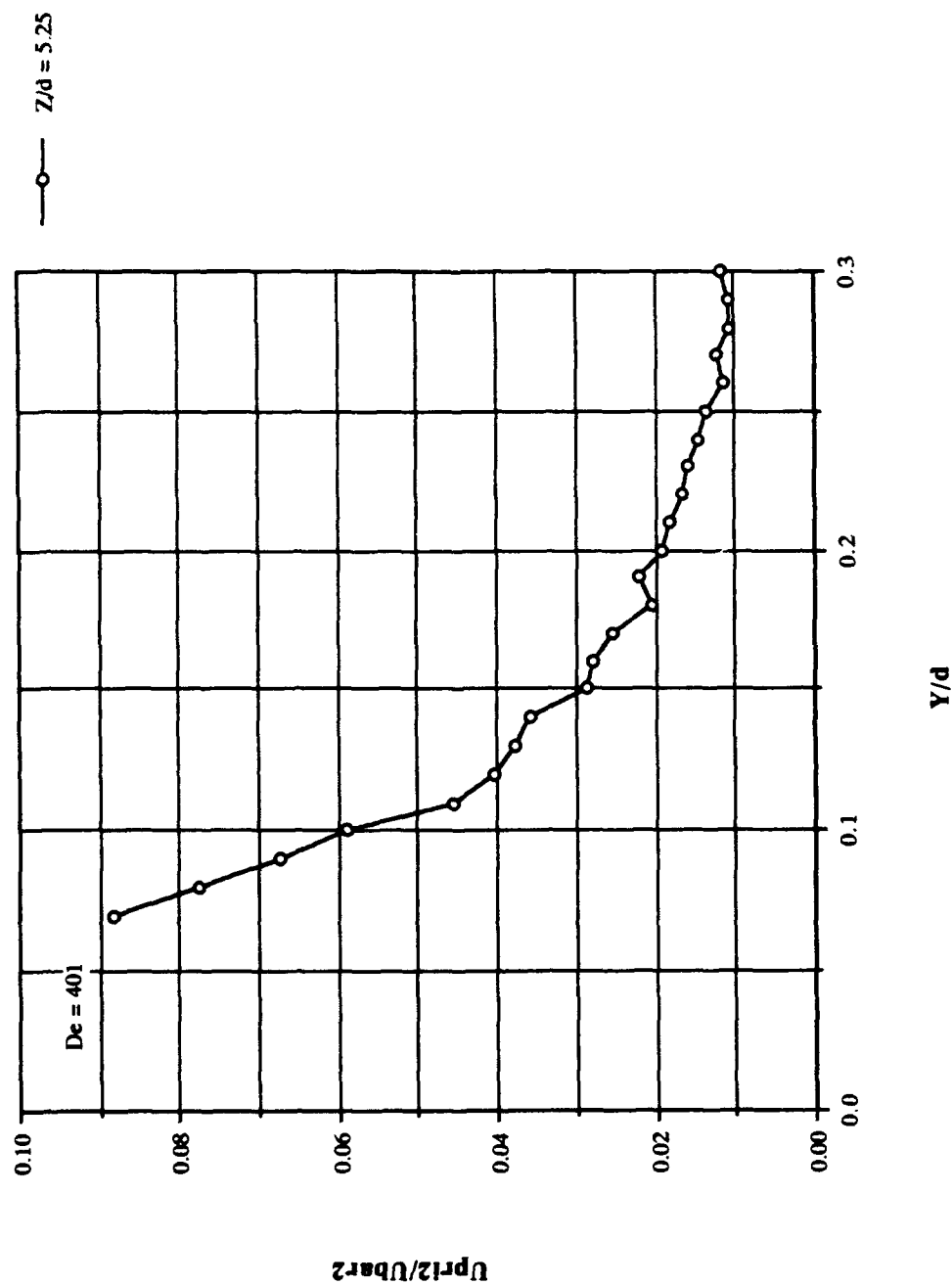
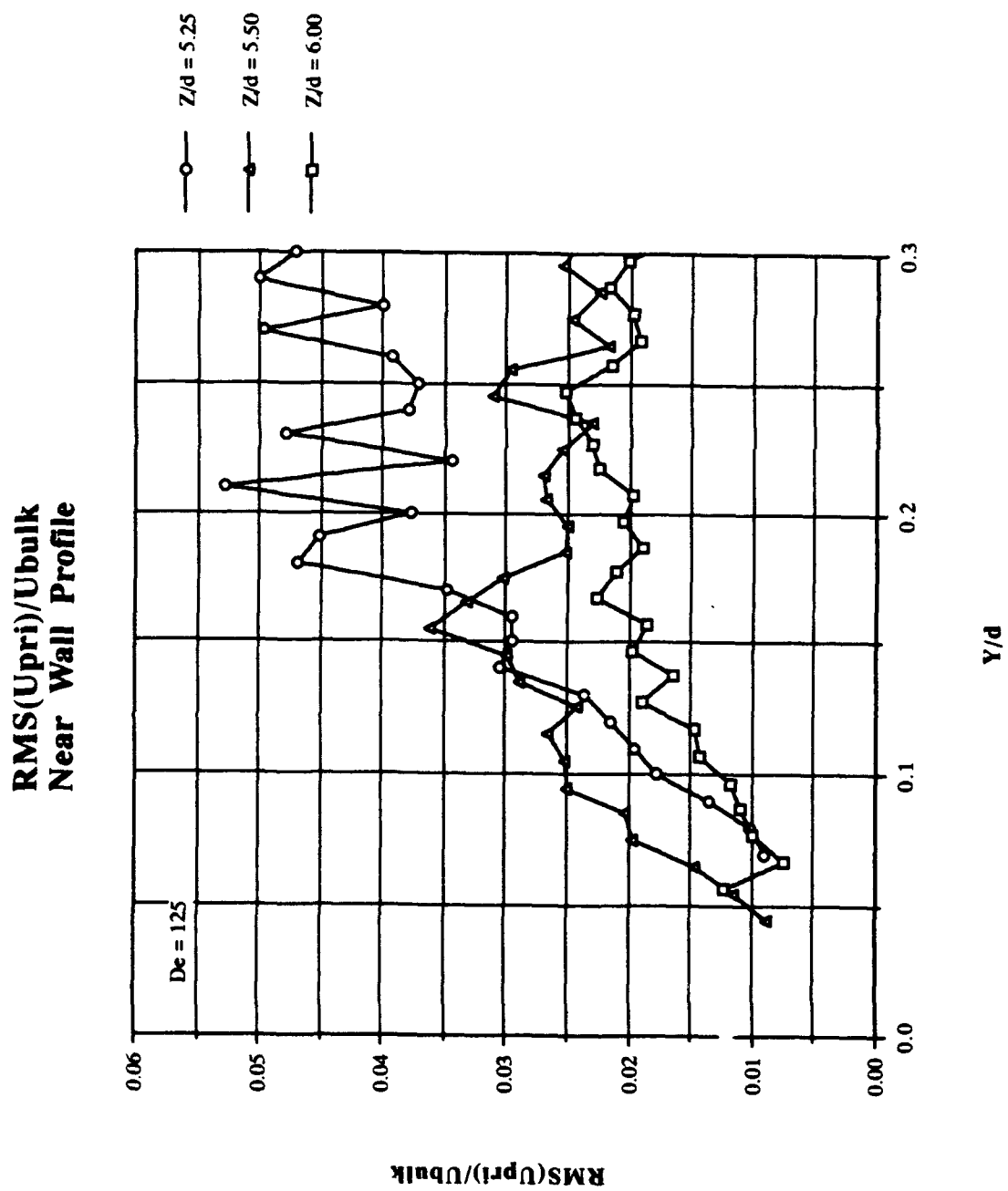


Figure 57. Normalized Longitudinal Reynolds Stress Profiles, De=401



**Figure 58. Normalized RMS Intensity,  $De=125$**

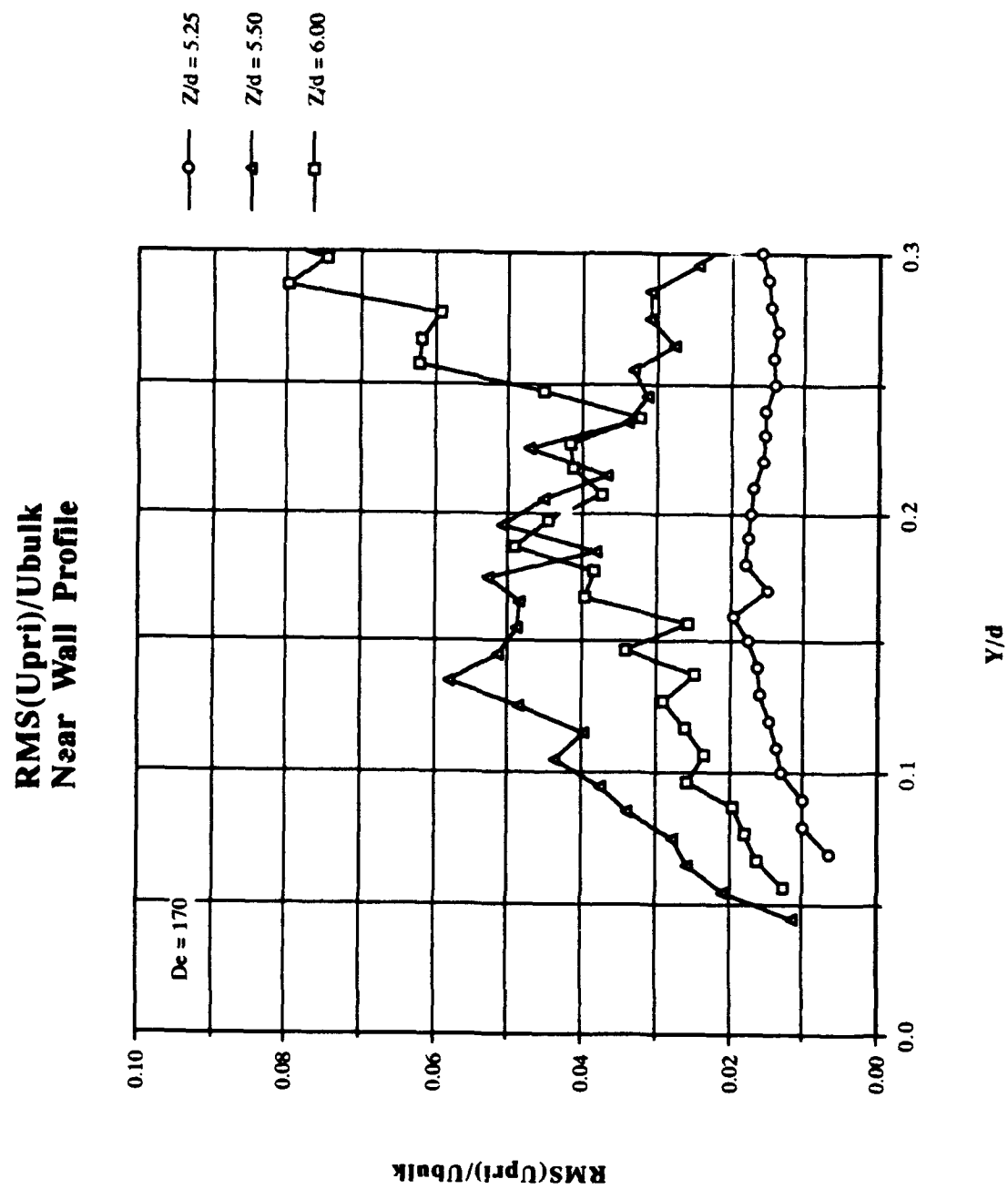
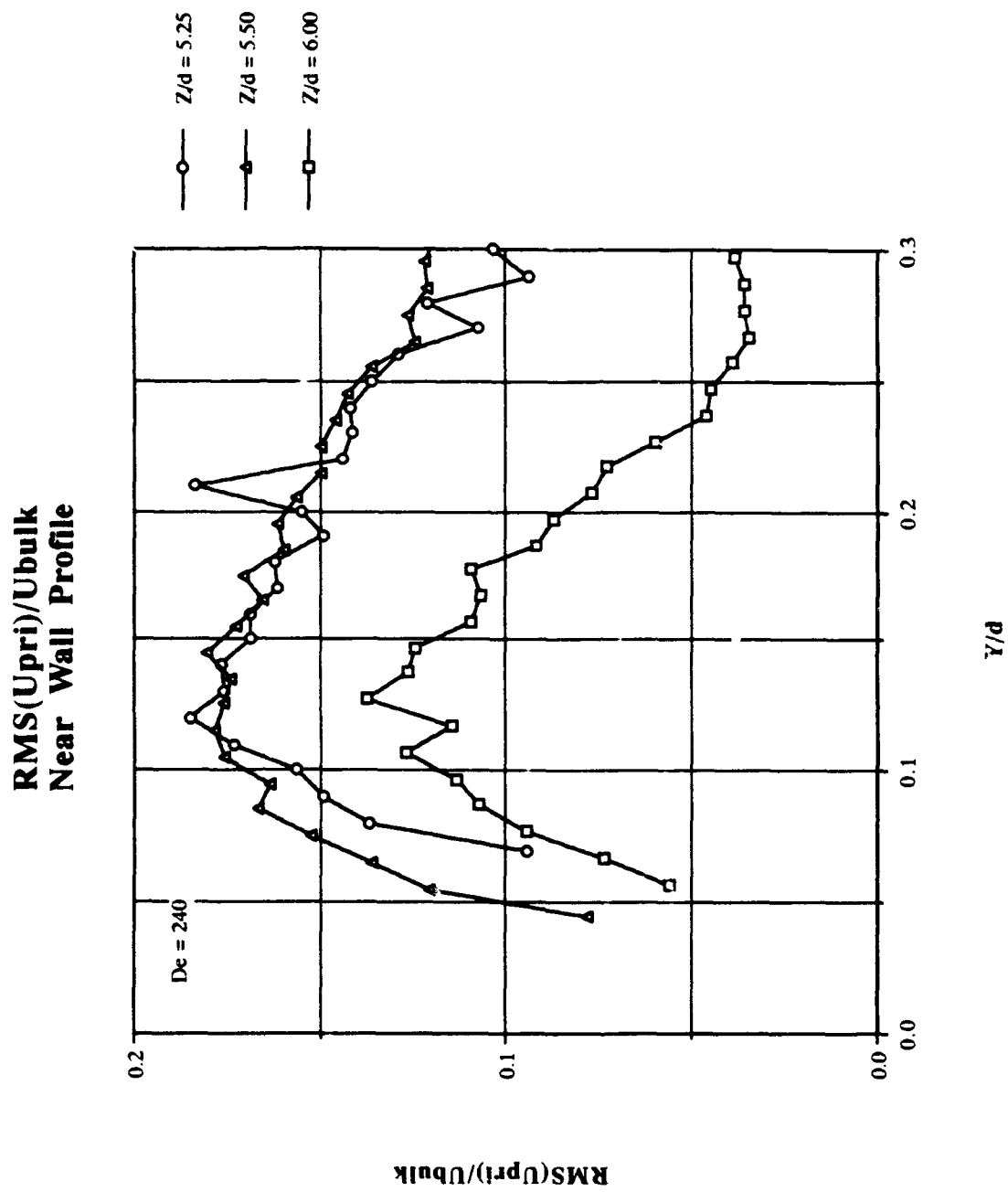
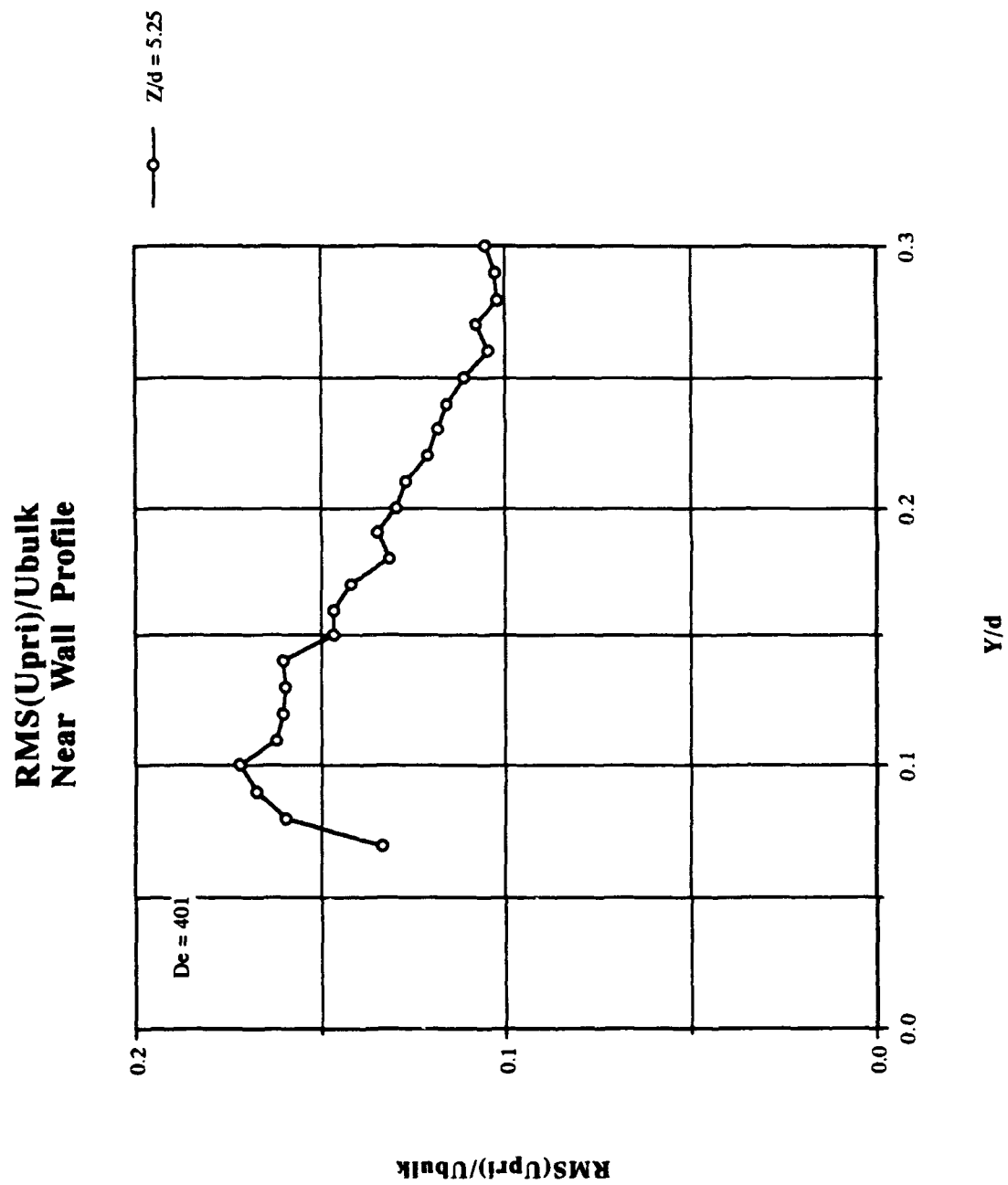


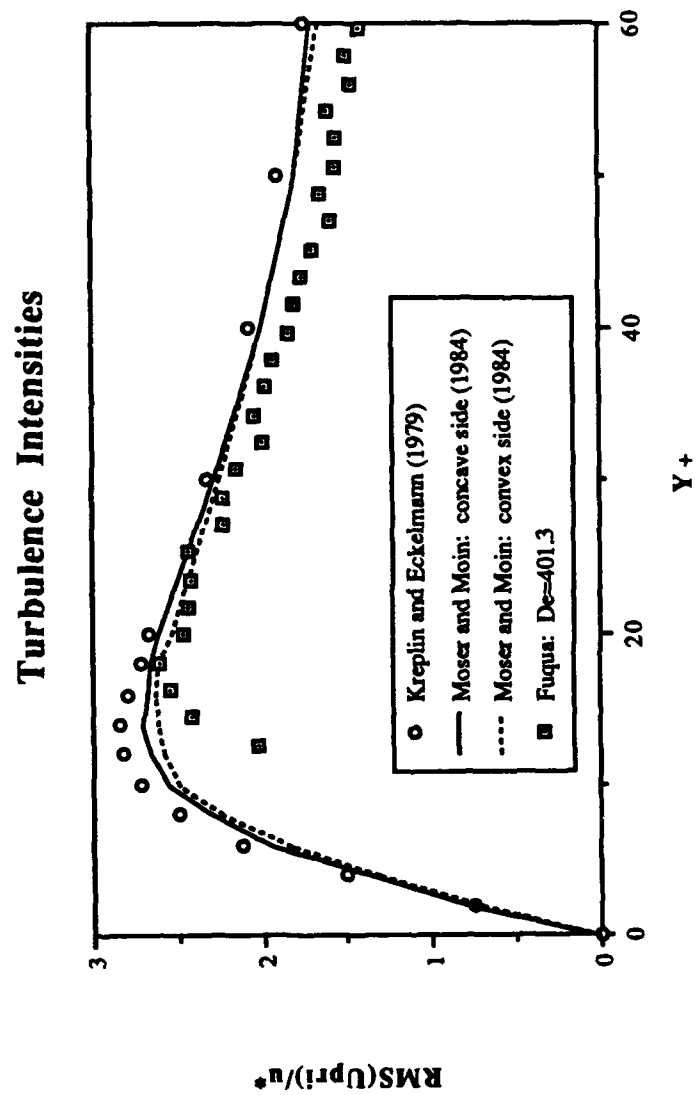
Figure 59. Normalized RMS Intensity,  $De=170$



**Figure 60. Normalized RMS Intensity,  $De=240$**

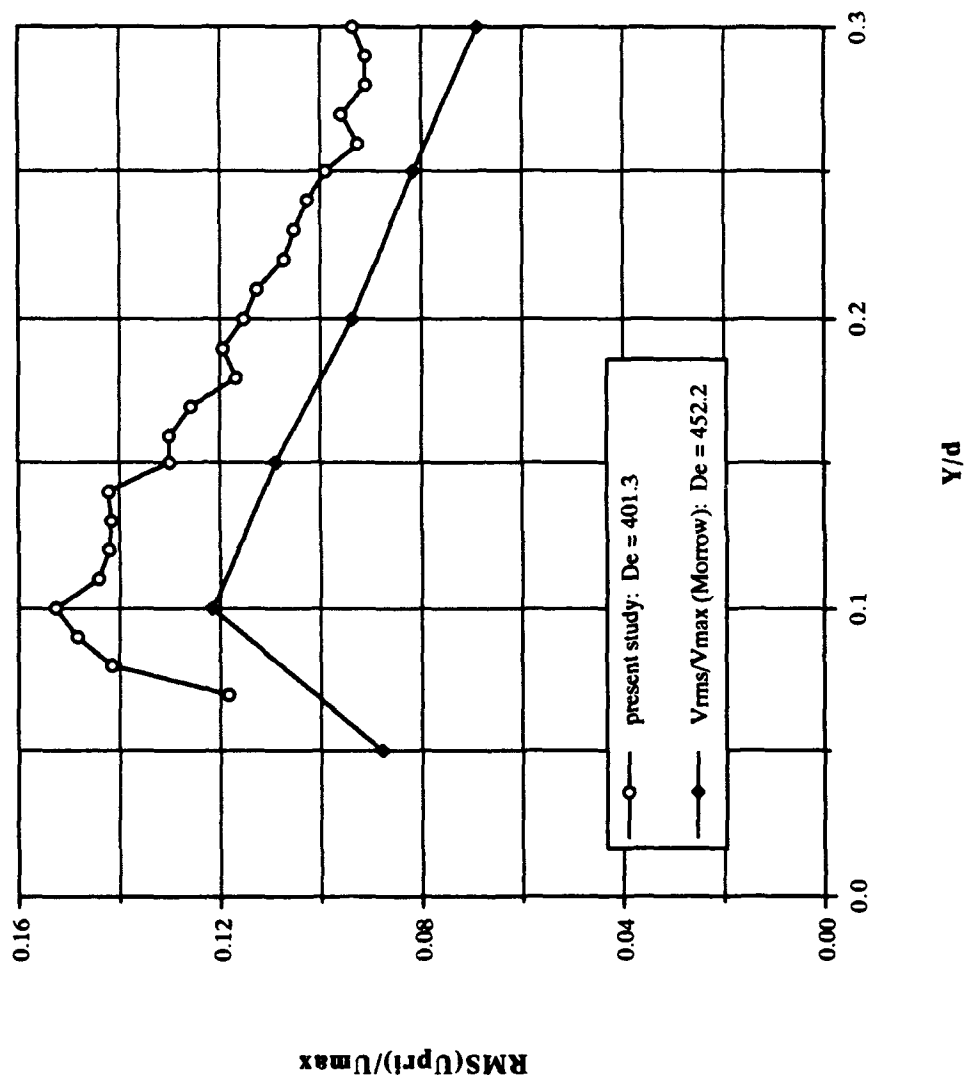


**Figure 61. Normalized RMS Intensity,  $De=401$**



**Figure 62. RMS Intensity Normalized by Friction Velocity,  $De=401$**

**RMS( $U_{pri}$ )/ $U_{max}$ : Near Wall Profile**



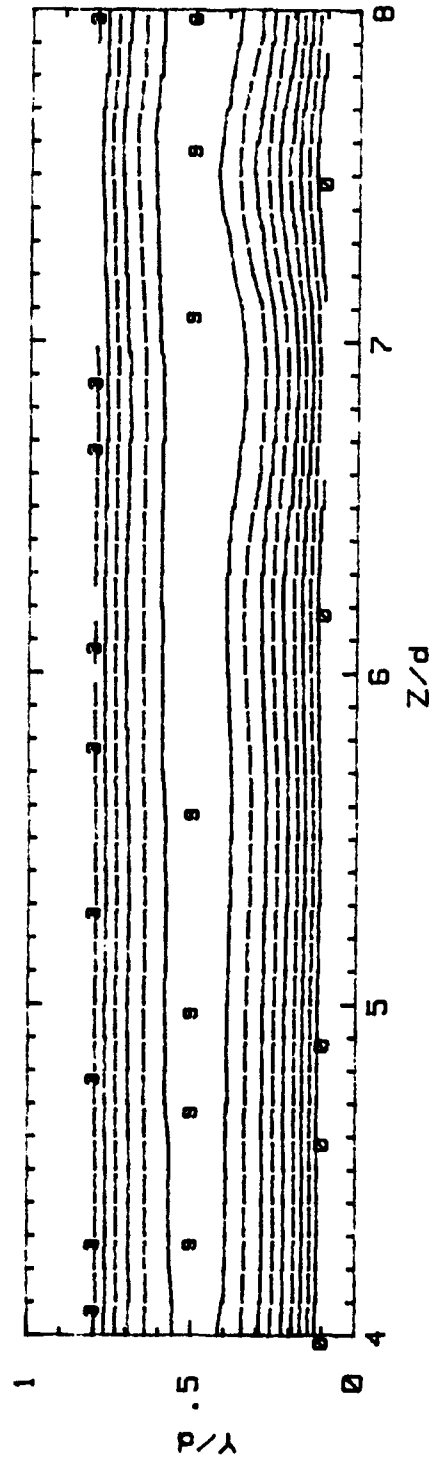
**Figure 63. RMS Intensity Normalized by the Maximum Velocity,  $De=401$**

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = .42 \text{ m/s}$   $De = 50.16$   $Re = 343.9$

RUN 052391.2209



### U (m/s) RANGES

0:	.232 TO .266	5:	.402 TO .436
1:	.266 TO .300	6:	.436 TO .470
2:	.300 TO .334	7:	.470 TO .504
3:	.334 TO .368	8:	.504 TO .538
4:	.368 TO .402	9:	.538 TO .572

Figure 64. Streamwise Mean Velocity Contour,  $De=50.2$

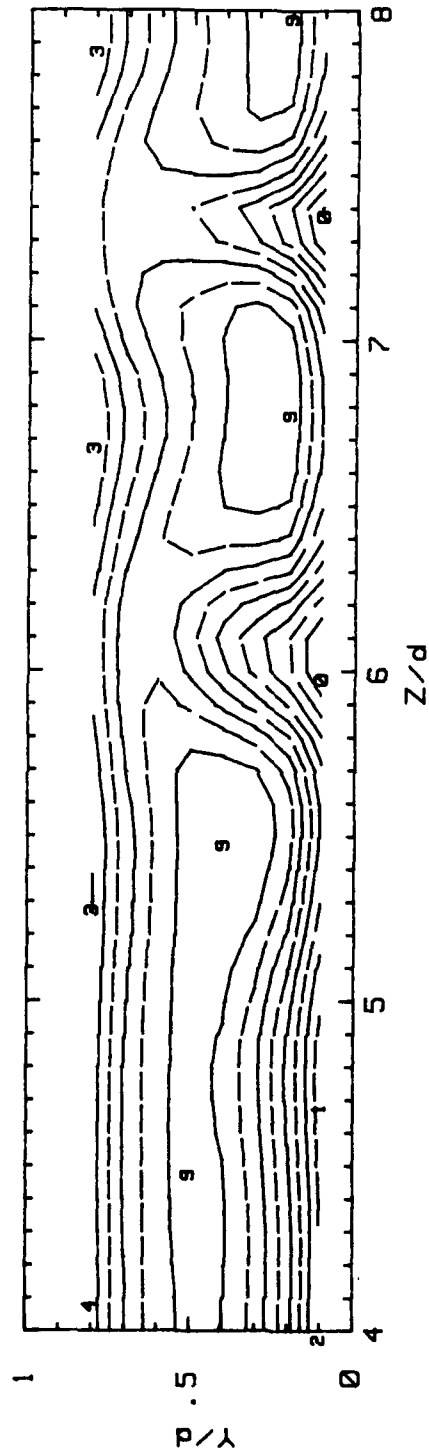


# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = .51 \text{ m/s}$   $De = 60.23$   $Re = 412.9$

RUN 052491.2201



### U (m/s) RANGES

0:	.191 TO .239	5:	.434 TO .483
1:	.239 TO .288	6:	.483 TO .531
2:	.288 TO .337	7:	.531 TO .580
3:	.337 TO .385	8:	.580 TO .629
4:	.385 TO .434	9:	.629 TO .677

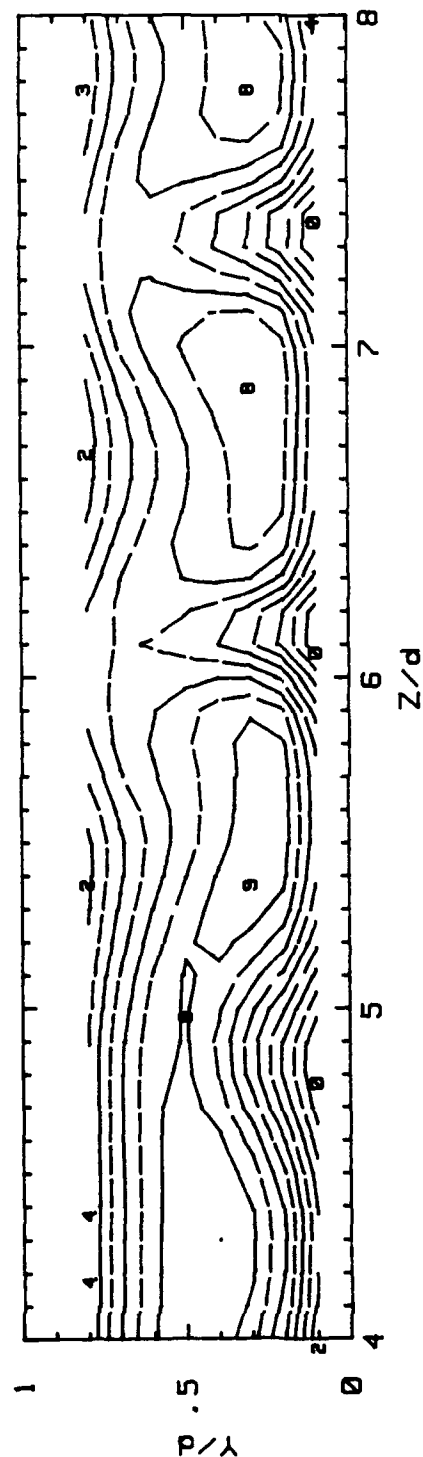
Figure 65. Streamwise Mean Velocity Contour,  $De=60.2$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = .59 \text{ m/s}$   $De = 70.22$   $Re = 481.4$

RUN 052591.2211



### U (m/s) RANGES

0:	.248 TO .301	5:	.514 TO .567
1:	.301 TO .354	6:	.567 TO .620
2:	.354 TO .407	7:	.620 TO .673
3:	.407 TO .461	8:	.673 TO .727
4:	.461 TO .514	9:	.727 TO .780

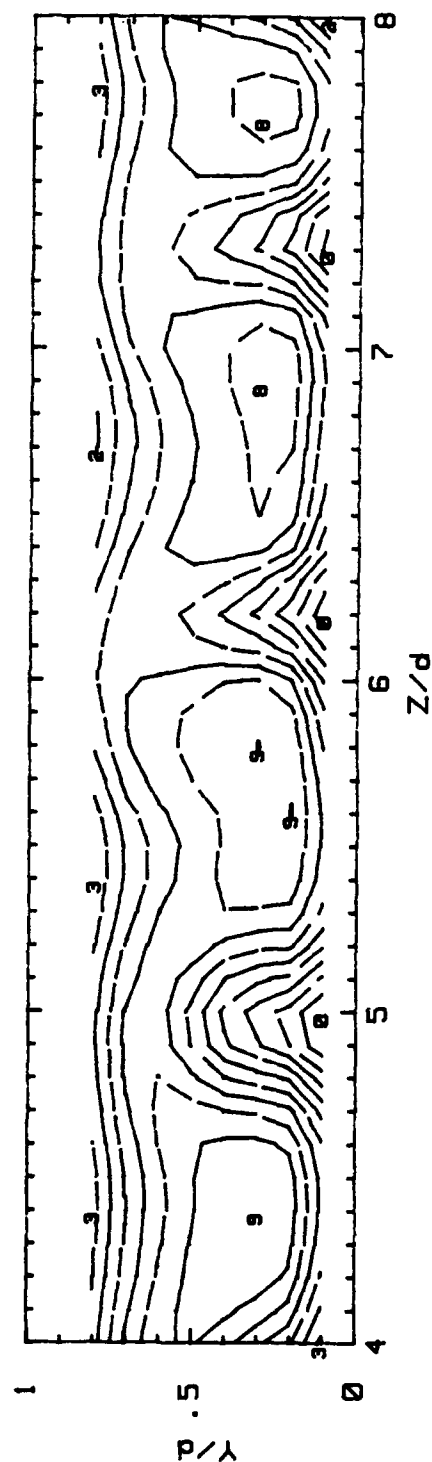
Figure 66. Streamwise Mean Velocity Contour,  $De=70.2$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = .67 \text{ m/s}$   $De = 80.31$   $Re = 550.6$

RUN 052691.2225



## U (m/s) RANGES

0: .244 TO .307	5: .560 TO .623
1: .307 TO .370	6: .623 TO .686
2: .370 TO .434	7: .686 TO .749
3: .434 TO .497	8: .749 TO .812
4: .497 TO .560	9: .812 TO .876

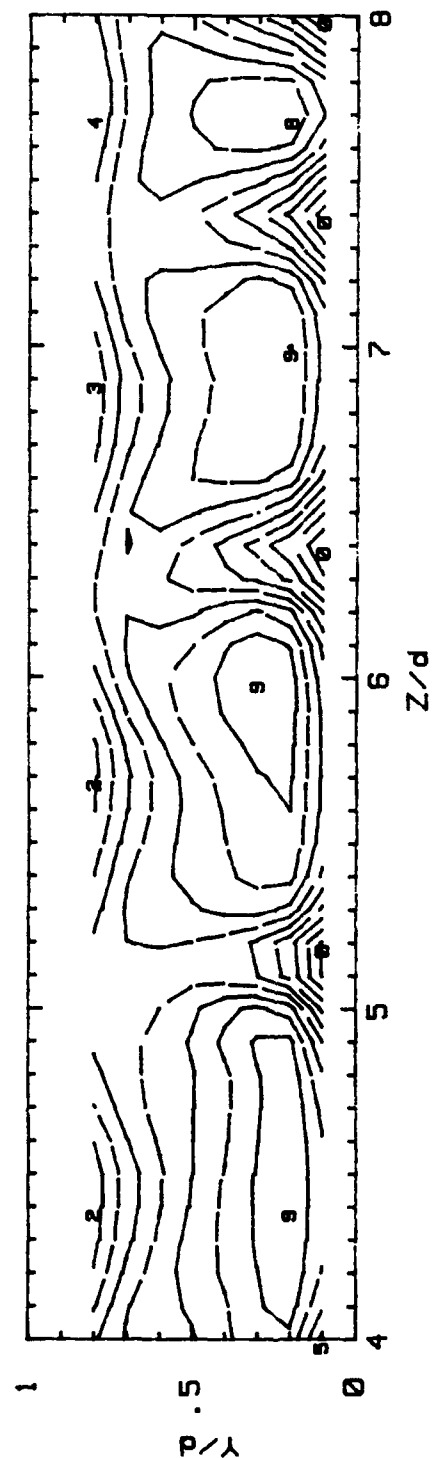
Figure 67. Streamwise Mean Velocity Contour,  $De=80.3$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = .76 \text{ m/s}$   $De = 90.36$   $Re = 619.5$

RUN 052791.2211



## U (m/s) RANGES

0: .310 TO .374	5: .631 TO .696
1: .374 TO .439	6: .696 TO .760
2: .439 TO .503	7: .760 TO .824
3: .503 TO .567	8: .824 TO .889
4: .567 TO .631	9: .889 TO .953

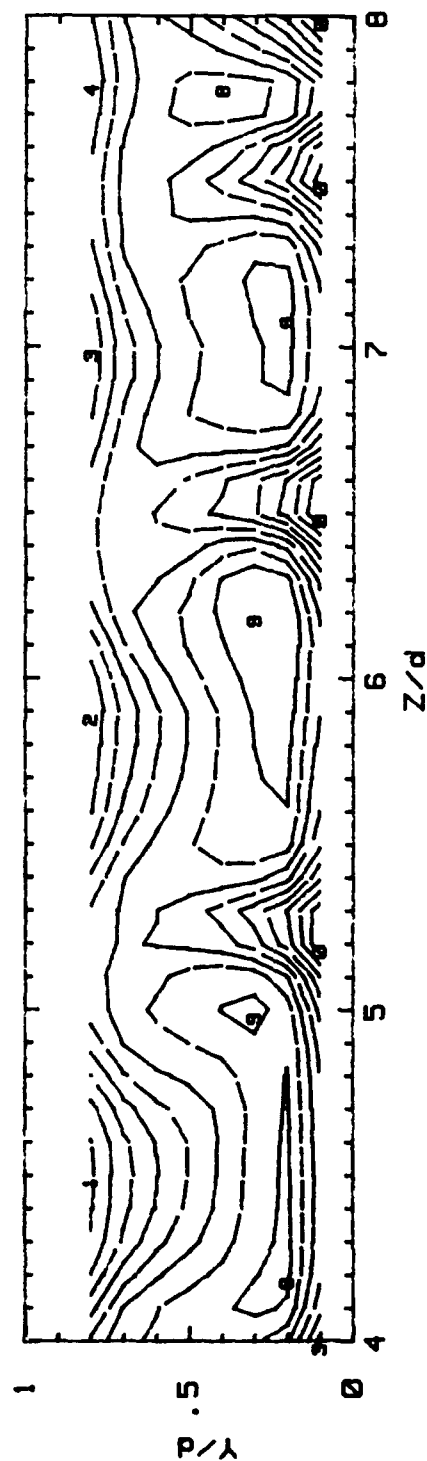
Figure 68. Streamwise Mean Velocity Contour,  $De=90.4$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = .84 \text{ m/s}$   $De = 100.4$   $Re = 688.1$

RUN 052891.2157



## U (m/s) RANGES

0:	0.38 TO 0.44	5:	0.70 TO 0.77
1:	0.44 TO 0.51	6:	0.77 TO 0.83
2:	0.51 TO 0.57	7:	0.83 TO 0.90
3:	0.57 TO 0.64	8:	0.90 TO 0.96
4:	0.64 TO 0.70	9:	0.96 TO 1.03

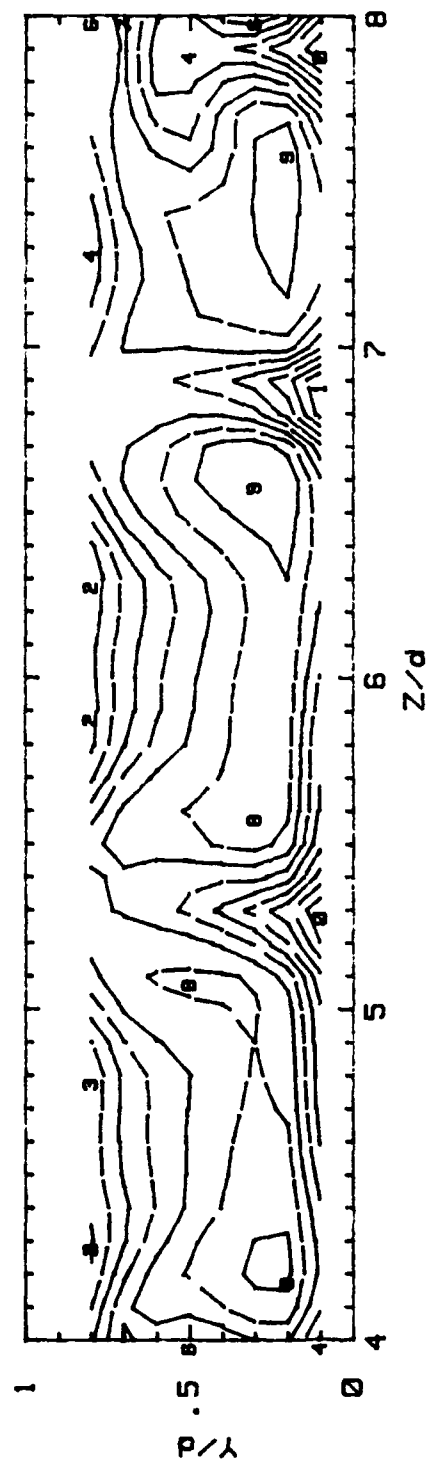
Figure 69. Streamwise Mean Velocity Contour,  $De=100.4$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 1.1 \text{ m/s}$   $De = 125.4$   $Re = 859.9$

RUN 053091.2157



### U (m/s) RANGES

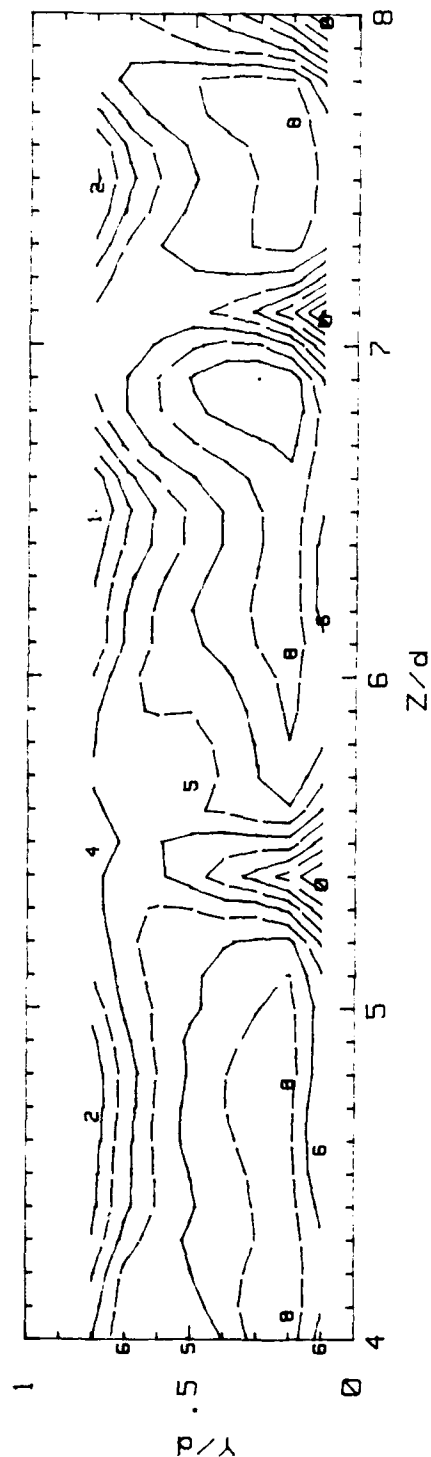
0: 0.45 TO 0.54	5: 0.88 TO 0.97
1: 0.54 TO 0.62	6: 0.97 TO 1.06
2: 0.62 TO 0.71	7: 1.06 TO 1.14
3: 0.71 TO 0.80	8: 1.14 TO 1.23
4: 0.80 TO 0.88	9: 1.23 TO 1.32

Figure 70. Streamwise Mean Velocity Contour,  $De=125.4$

Streamwise Mean Velocity  
CURVED CHANNEL

$U_{bulk} = 1.3 \text{ m/s}$   $De = 150.6$   $Re = 1032$

RUN 053191.2201



U (m/s) RANGES

0:	0.56 TO 0.67	5:	1.09 TO 1.19
1:	0.67 TO 0.77	6:	1.19 TO 1.30
2:	0.77 TO 0.88	7:	1.30 TO 1.40
3:	0.88 TO 0.98	8:	1.40 TO 1.51
4:	0.98 TO 1.09	9:	1.51 TO 1.61

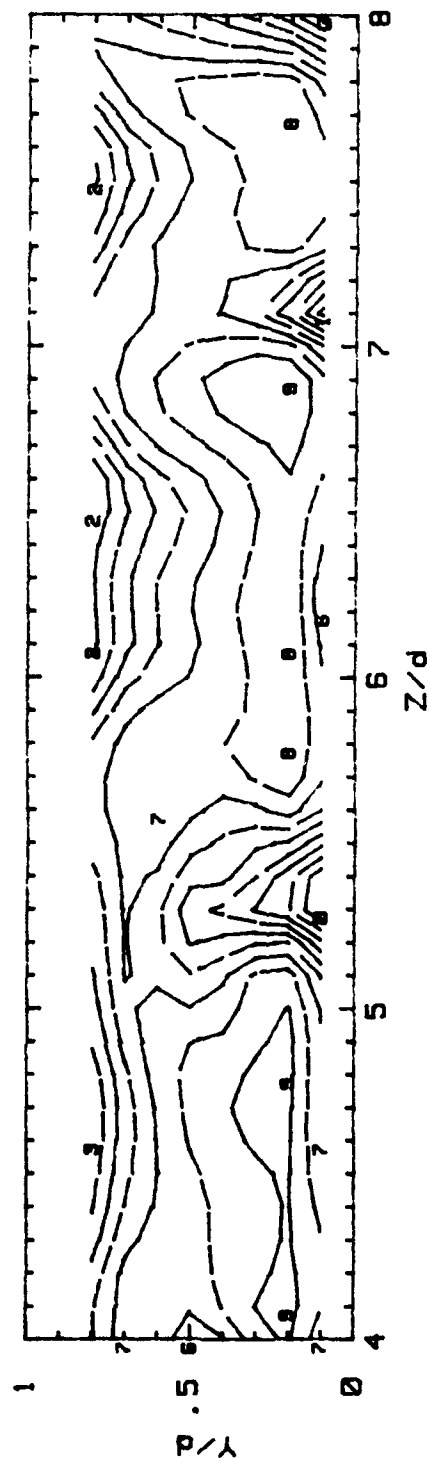
Figure 71. Streamwise Mean Velocity Contour,  $De=150.6$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 1.3 \text{ m/s}$   $De = 160.5$   $Re = 1101$

RUN 052991.2155



### U (m/s) RANGES

0: 0.55 TO 0.66	5: 1.08 TO 1.19
1: 0.66 TO 0.76	6: 1.19 TO 1.30
2: 0.76 TO 0.87	7: 1.30 TO 1.41
3: 0.87 TO 0.98	8: 1.41 TO 1.51
4: 0.98 TO 1.08	9: 1.51 TO 1.62

Figure 72. Streamwise Mean Velocity Contour,  $De=160.5$

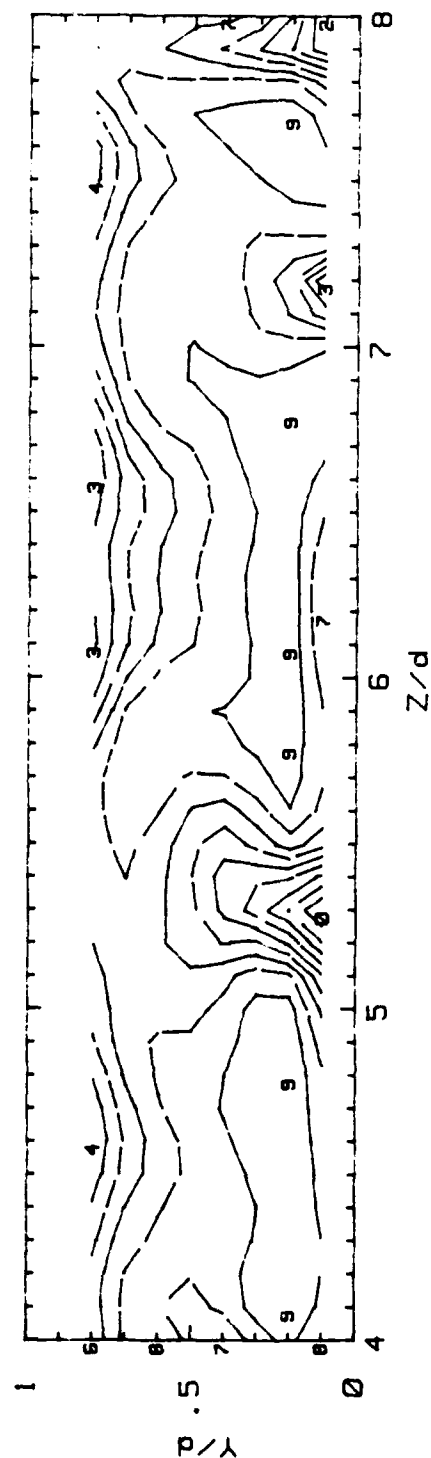


# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 1.4 \text{ m/s}$   $De = 170.6$   $Re = 1170$

RUN 060191.2157



### U (m/s) RANGES

0:	0.52 TO 0.64	5:	1.09 TO 1.21
1:	0.64 TO 0.75	6:	1.21 TO 1.32
2:	0.75 TO 0.86	7:	1.32 TO 1.43
3:	0.86 TO 0.98	8:	1.43 TO 1.55
4:	0.98 TO 1.09	9:	1.55 TO 1.66

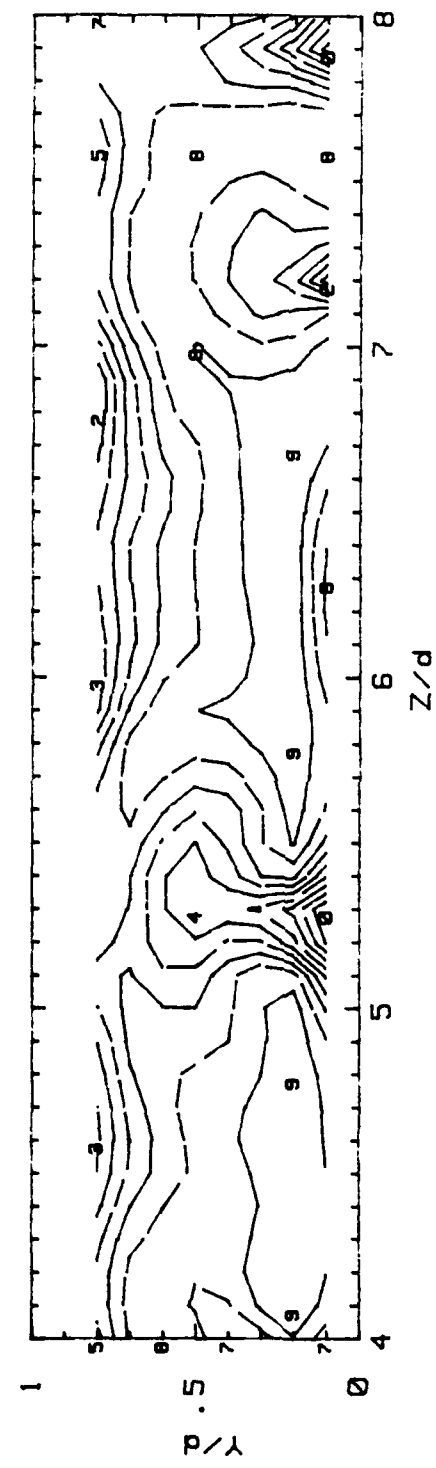
Figure 73. Streamwise Mean Velocity Contour,  $De=170.6$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 1.5 \text{ m/s}$   $De = 180.7$   $Re = 1239$

RUN 060291.2151



### U (m/s) RANGES

0:	0.69 TO 0.80	5:	1.21 TO 1.32
1:	0.80 TO 0.90	6:	1.32 TO 1.42
2:	0.90 TO 1.01	7:	1.42 TO 1.53
3:	1.01 TO 1.11	8:	1.53 TO 1.63
4:	1.11 TO 1.21	9:	1.63 TO 1.74

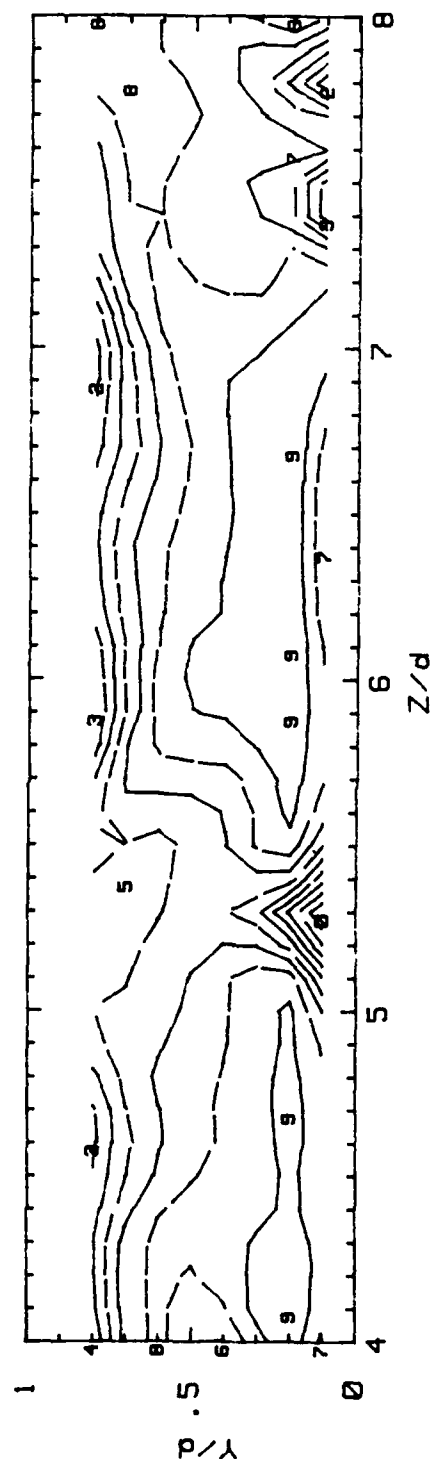
Figure 74. Streamwise Mean Velocity Contour,  $De=180.7$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 1.6 \text{ m/s}$   $De = 190.7$   $Re = 1307$

RUN 060391.2156



## U (m/s) RANGES

0: 0.72 TO 0.83	5: 1.28 TO 1.39
1: 0.83 TO 0.94	6: 1.39 TO 1.51
2: 0.94 TO 1.05	7: 1.51 TO 1.62
3: 1.05 TO 1.17	8: 1.62 TO 1.73
4: 1.17 TO 1.28	9: 1.73 TO 1.85

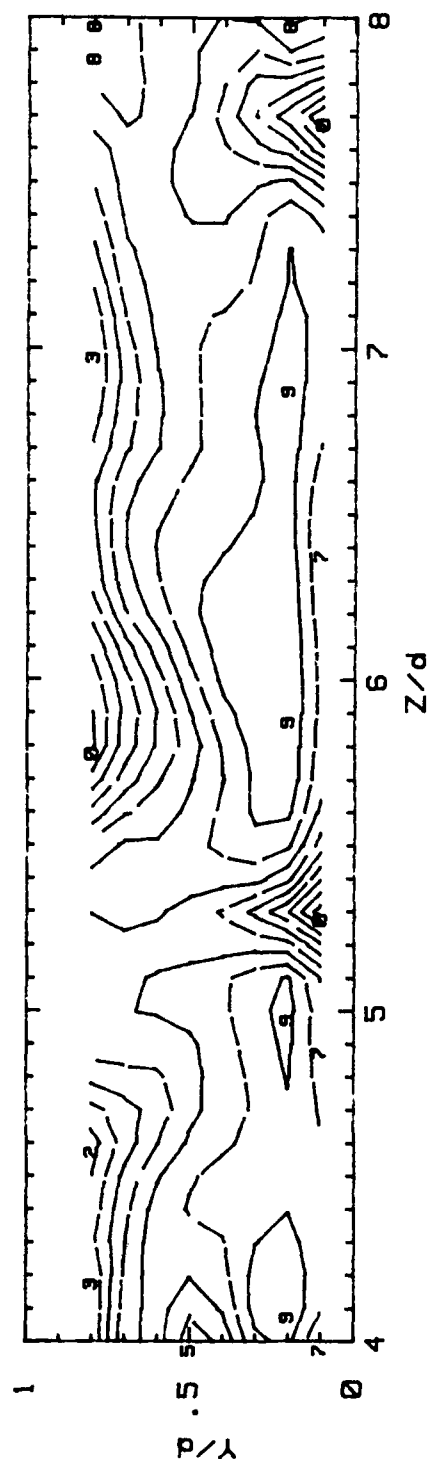
Figure 75. Streamwise Mean Velocity Contour,  $De=190.7$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 1.7 \text{ m/s}$   $De = 200.7$   $Re = 1376$

RUN 060491.2207



### U (m/s) RANGES

0: 0.81 TO 0.93	5: 1.42 TO 1.54
1: 0.93 TO 1.05	6: 1.54 TO 1.67
2: 1.05 TO 1.18	7: 1.67 TO 1.79
3: 1.18 TO 1.30	8: 1.79 TO 1.91
4: 1.30 TO 1.42	9: 1.91 TO 2.03

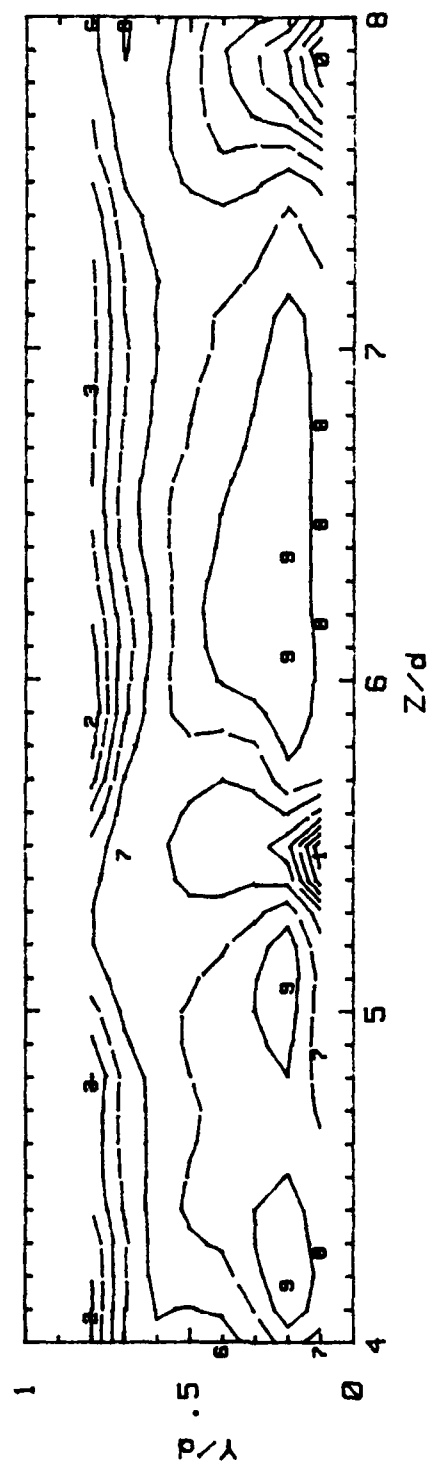
Figure 76. Streamwise Mean Velocity Contour,  $De=200.7$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 1.9 \text{ m/s}$   $De = 225.7$   $Re = 1548$

RUN 060591.2211



## U (m/s) RANGES

0: 1.05 TO 1.16	5: 1.60 TO 1.71
1: 1.16 TO 1.27	6: 1.71 TO 1.82
2: 1.27 TO 1.38	7: 1.82 TO 1.93
3: 1.38 TO 1.49	8: 1.93 TO 2.04
4: 1.49 TO 1.60	9: 2.04 TO 2.15

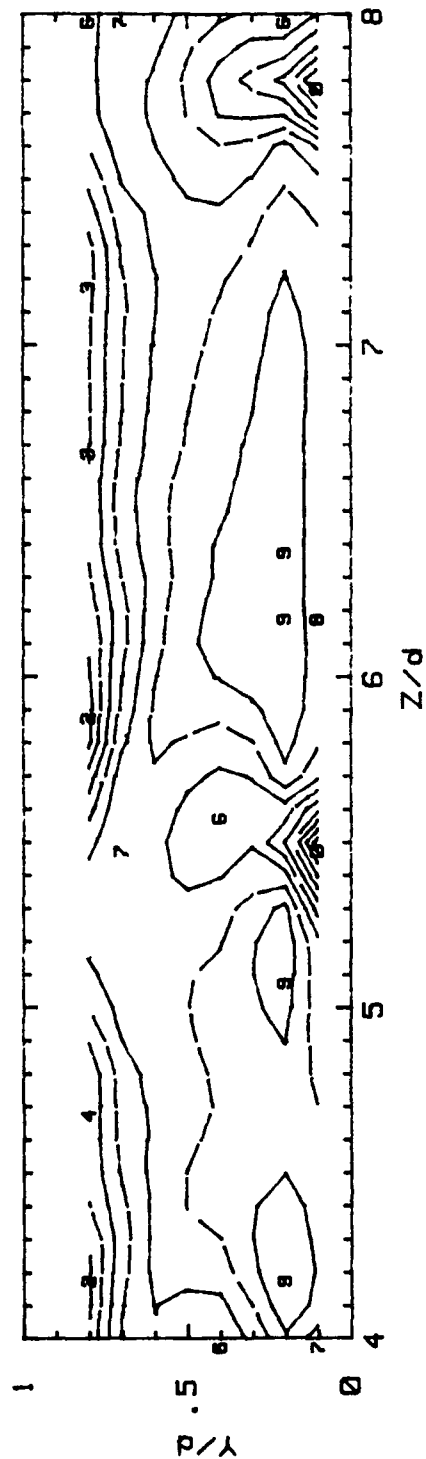
Figure 77. Streamwise Mean Velocity Contour,  $De=225.7$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 1.9 \text{ m/s}$   $De = 230.8$   $Re = 1582$

RUN 060691.2205



### U (m/s) RANGES

0:	1.00 TO 1.12	5:	1.59 TO 1.70
1:	1.12 TO 1.24	6:	1.70 TO 1.82
2:	1.24 TO 1.35	7:	1.82 TO 1.93
3:	1.35 TO 1.47	8:	1.93 TO 2.05
4:	1.47 TO 1.59	9:	2.05 TO 2.17

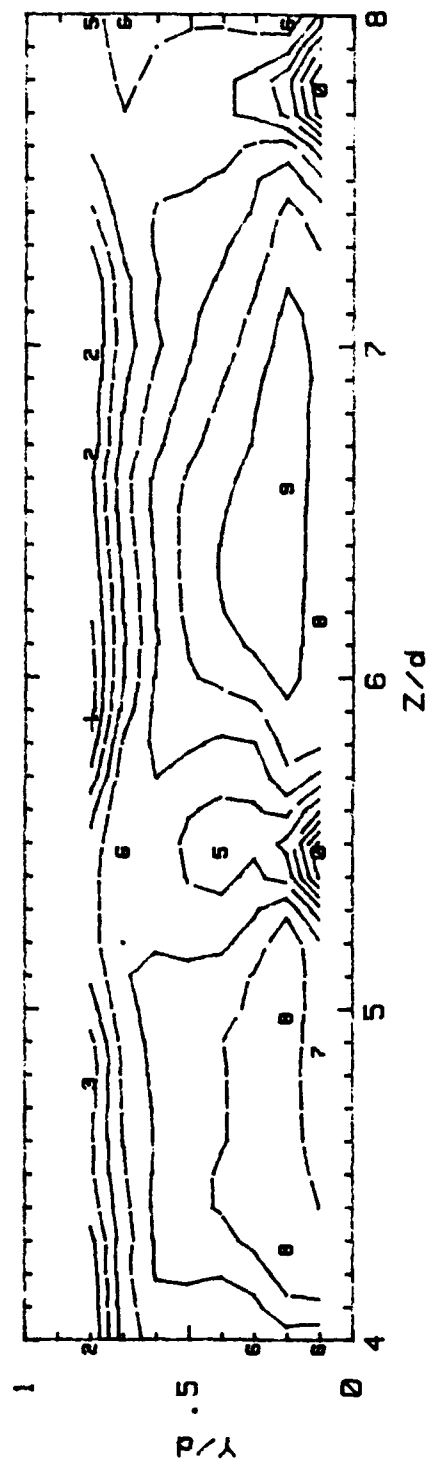
Figure 78. Streamwise Mean Velocity Contour,  $De=230.8$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 2 \text{ m/s}$   $De = 240.8$   $Re = 1651$

RUN 060791.2159



### U (m/s) RANGES

0:	1.25 TO 1.36	5:	1.77 TO 1.87
1:	1.36 TO 1.46	6:	1.87 TO 1.97
2:	1.46 TO 1.56	7:	1.97 TO 2.07
3:	1.56 TO 1.66	8:	2.07 TO 2.17
4:	1.66 TO 1.77	9:	2.17 TO 2.28

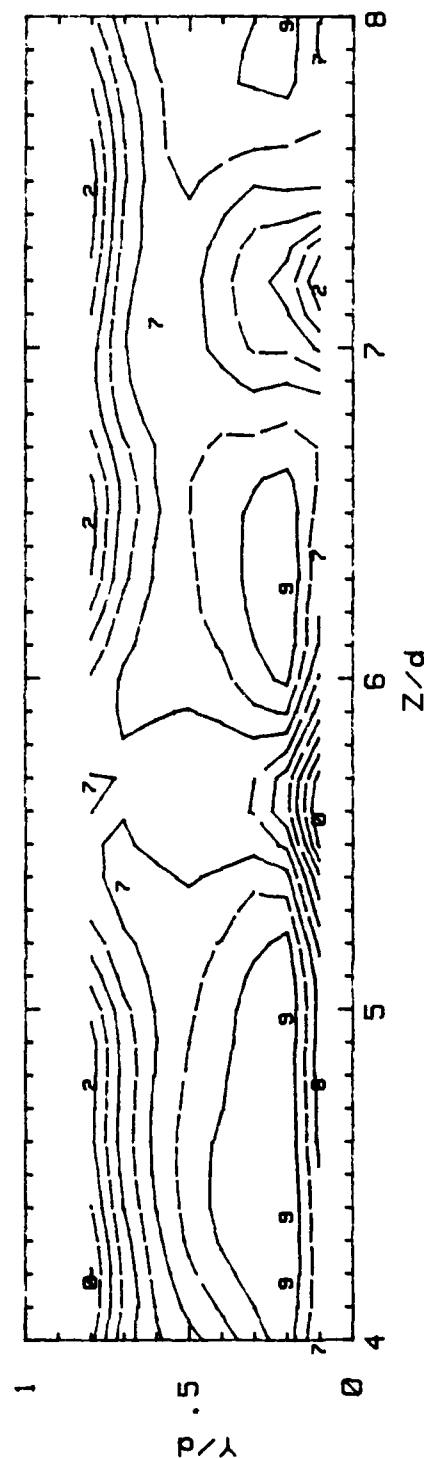
Figure 79. Streamwise Mean Velocity Contour,  $De=240.8$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 2.1 \text{ m/s}$   $De = 250.8$   $Re = 1719$

RUN 070391.2145



## U (m/s) RANGES

0:	1.30 TO 1.41	5:	1.84 TO 1.95
1:	1.41 TO 1.51	6:	1.95 TO 2.06
2:	1.51 TO 1.62	7:	2.06 TO 2.17
3:	1.62 TO 1.73	8:	2.17 TO 2.28
4:	1.73 TO 1.84	9:	2.28 TO 2.39

Figure 80. Streamwise Mean Velocity Contour,  $De=250.8$

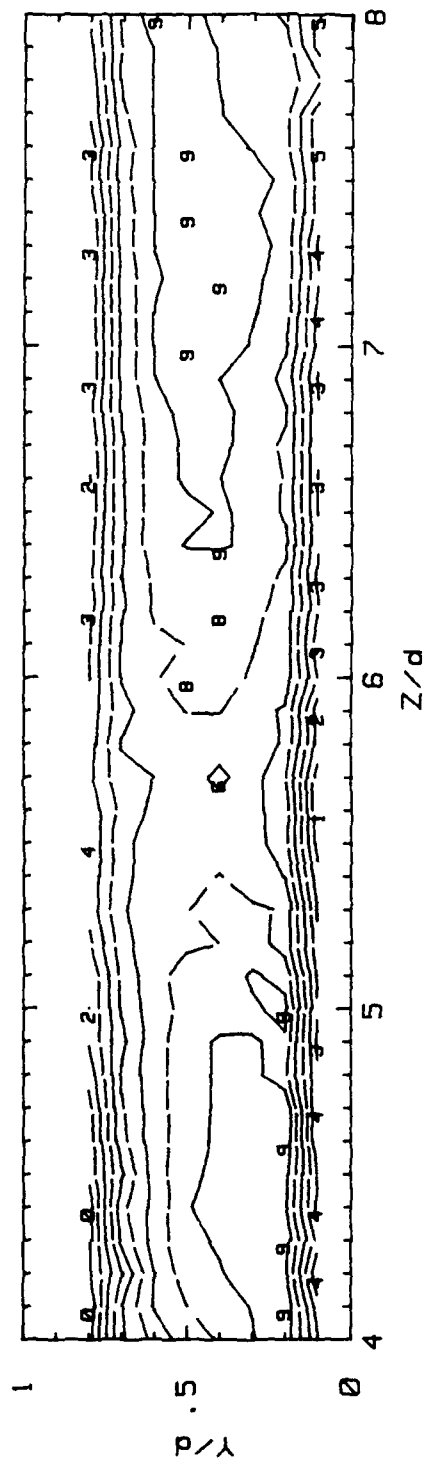


# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 2.2 \text{ m/s}$   $De = 263.3$   $Re = 1805$

RUN 070591.2201



### U (m/s) RANGES

0: 1.70 TO 1.77	5: 2.07 TO 2.14
1: 1.77 TO 1.85	6: 2.14 TO 2.22
2: 1.85 TO 1.92	7: 2.22 TO 2.29
3: 1.92 TO 1.99	8: 2.29 TO 2.37
4: 1.99 TO 2.07	9: 2.37 TO 2.44

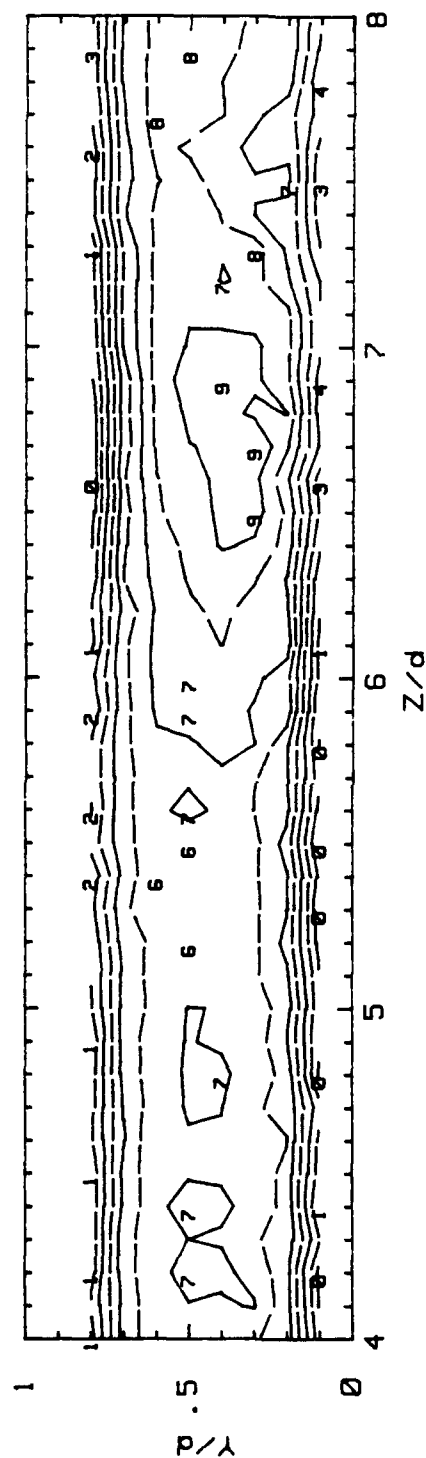
Figure 81. Streamwise Mean Velocity Contour,  $De=263.3$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 2.3 \text{ m/s}$   $De = 275.9$   $Re = 1892$

RUN 070691.2155



### U (m/s) RANGES

0:	1.91 TO 1.98	5:	2.26 TO 2.33
1:	1.98 TO 2.05	6:	2.33 TO 2.40
2:	2.05 TO 2.12	7:	2.40 TO 2.47
3:	2.12 TO 2.19	8:	2.47 TO 2.54
4:	2.19 TO 2.26	9:	2.54 TO 2.61

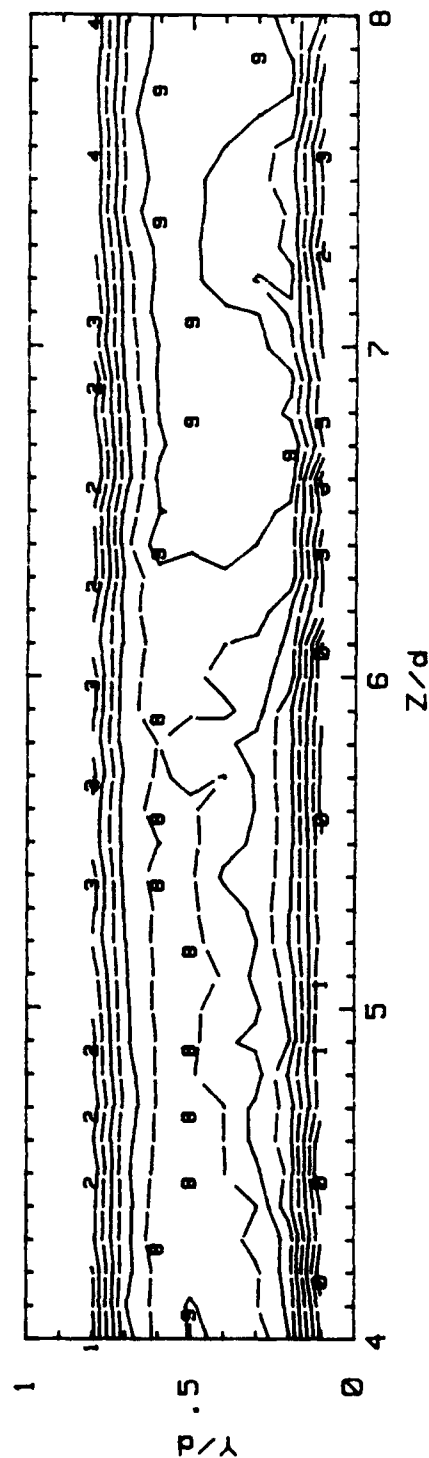
Figure 82. Streamwise Mean Velocity Contour,  $De=275.9$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 2.5 \text{ m/s}$   $De = 301$   $Re = 2063$

RUN 070791.2154



### U (m/s) RANGES

0:	2.23 TO 2.30	5:	2.55 TO 2.62
1:	2.30 TO 2.36	6:	2.62 TO 2.68
2:	2.36 TO 2.43	7:	2.68 TO 2.74
3:	2.43 TO 2.49	8:	2.74 TO 2.81
4:	2.49 TO 2.55	9:	2.81 TO 2.87

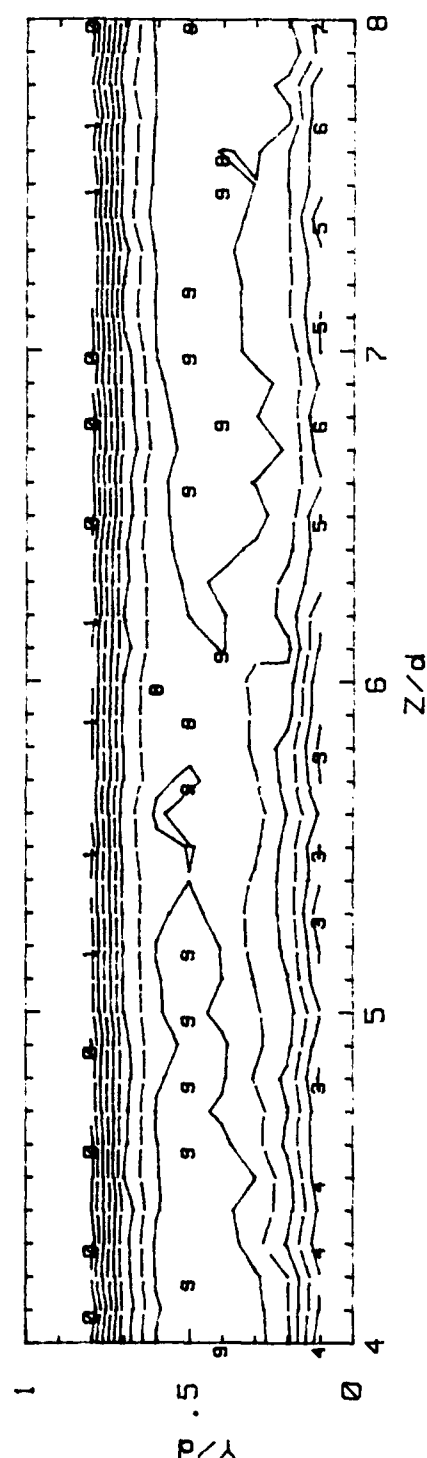
Figure 83. Streamwise Mean Velocity Contour,  $De=301.0$

# Streamwise Mean Velocity

CURVED CHANNEL - TC

$U_{bulk} = 2.7 \text{ m/s}$   $De = 326.1$   $Re = 2236$

RUN 071791.2157

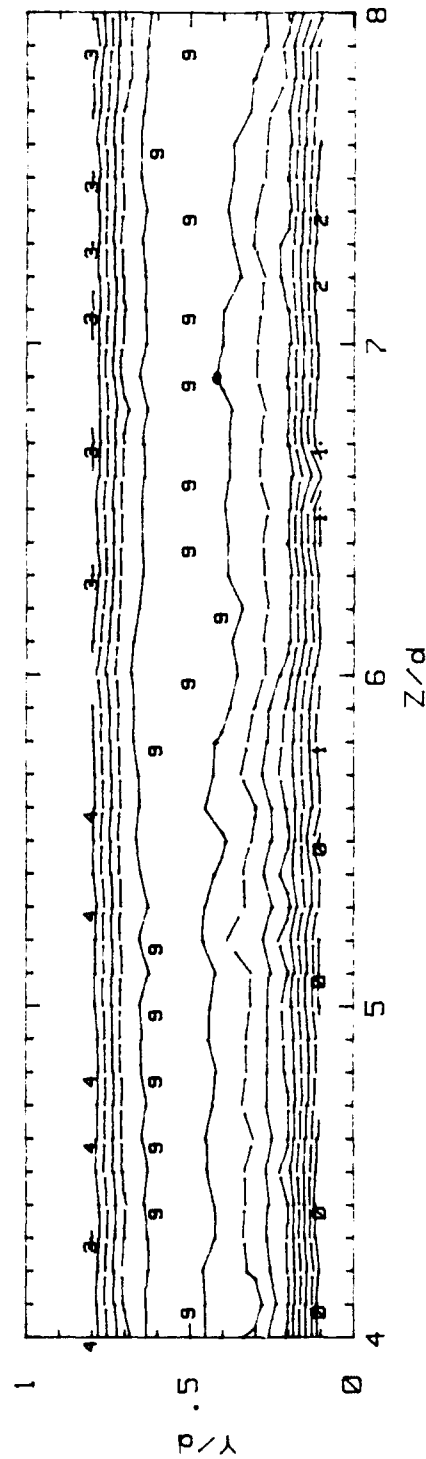


U (m/s) RANGES

0:	2.31 TO 2.39	5:	2.68 TO 2.76
1:	2.39 TO 2.46	6:	2.76 TO 2.83
2:	2.46 TO 2.54	7:	2.83 TO 2.91
3:	2.54 TO 2.61	8:	2.91 TO 2.98
4:	2.61 TO 2.68	9:	2.98 TO 3.06

Figure 84. Streamwise Mean Velocity Contour,  $De=326.1$

Streamwise Mean Velocity  
 CURVED CHANNEL - TC  
 $U_{bulk} = 2.9 \text{ m/s}$   $De = 351.1$   $Re = 2407$   
 RUN 070991.2135



U (m/s) RANGES	
0: 2.68 TO 2.75	5: 3.03 TO 3.10
1: 2.75 TO 2.82	6: 3.10 TO 3.17
2: 2.82 TO 2.89	7: 3.17 TO 3.24
3: 2.89 TO 2.96	8: 3.24 TO 3.31
4: 2.96 TO 3.03	9: 3.31 TO 3.38

Figure 85. Streamwise Mean Velocity Contour,  $De=351.1$

# Streamwise Mean Velocity

CURVED CHANNEL - TC

$U_{bulk} = 3.2 \text{ m/s}$   $De = 376.2$   $Re = 2579$

RUN 071091.2151

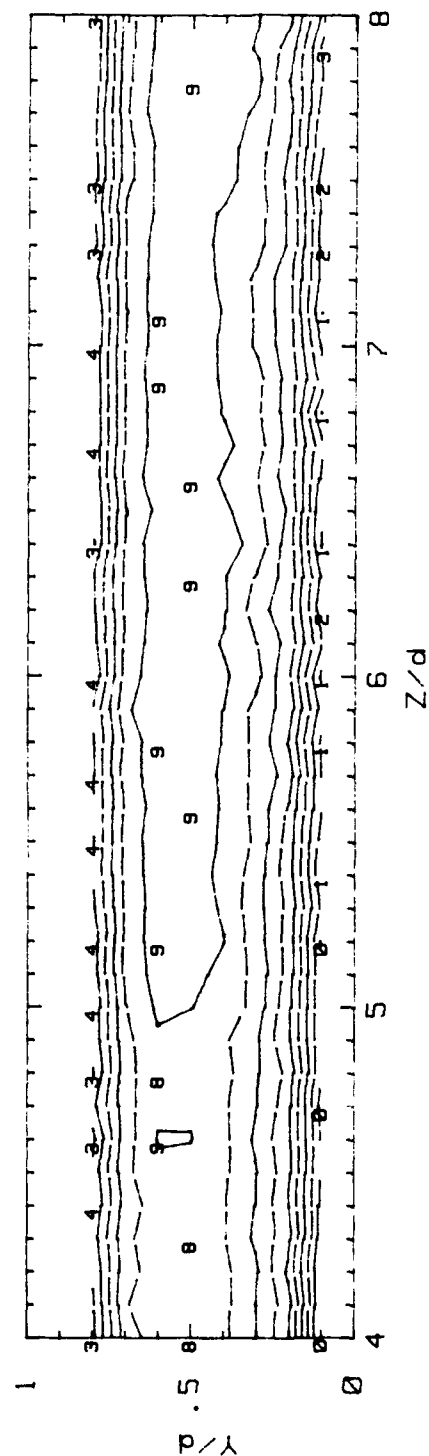


Figure 86. Streamwise Mean Velocity Contour,  $De=376.2$

# Streamwise Mean Velocity

CURVED CHANNEL - TC

$U_{bulk} = 3.4 \text{ m/s}$   $De = 401.3$   $Re = 2751$

RUN 071891.2201

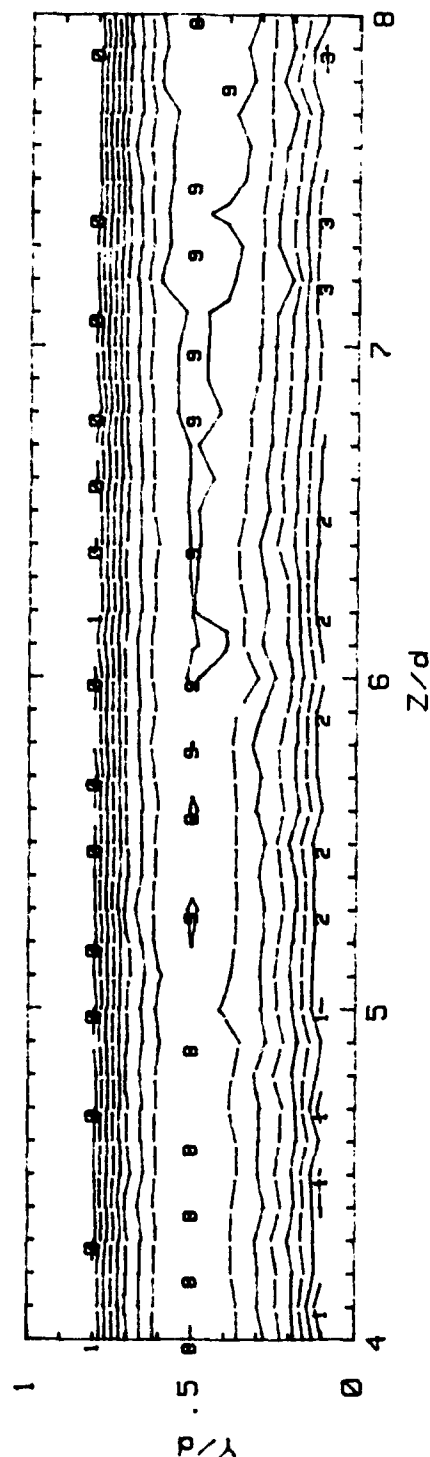


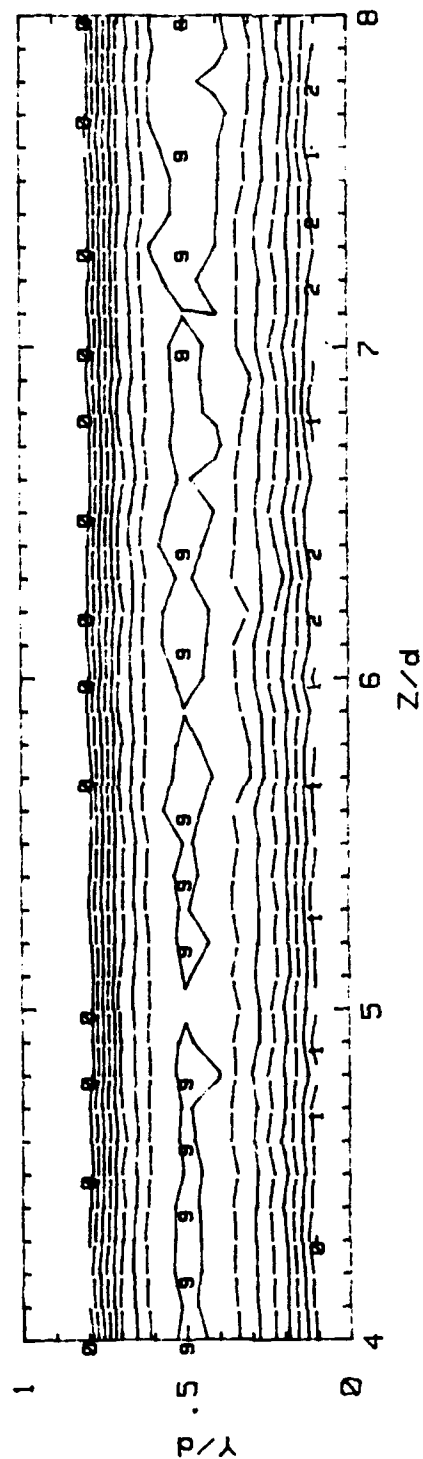
Figure 87. Streamwise Mean Velocity Contour,  $De=401.3$

# Streamwise Mean Velocity

CURVED CHANNEL - TC

$U_{bulk} = 3.6 \text{ m/s}$   $De = 426.4$   $Re = 2923$

RUN 071991.2202



$U \text{ (m/s) RANGES}$

0:	3.25 TO 3.32	5:	3.62 TO 3.69
1:	3.32 TO 3.40	6:	3.69 TO 3.77
2:	3.40 TO 3.47	7:	3.77 TO 3.84
3:	3.47 TO 3.54	8:	3.84 TO 3.91
4:	3.54 TO 3.62	9:	3.91 TO 3.99

Figure 88. Streamwise Mean Velocity Contour,  $De=426.4$



# Streamwise Mean Velocity

CURVED CHANNEL - TC

$U_{bulk} = 3.8 \text{ m/s}$   $De = 451.5$   $Re = 3095$

RUN 072091.2201

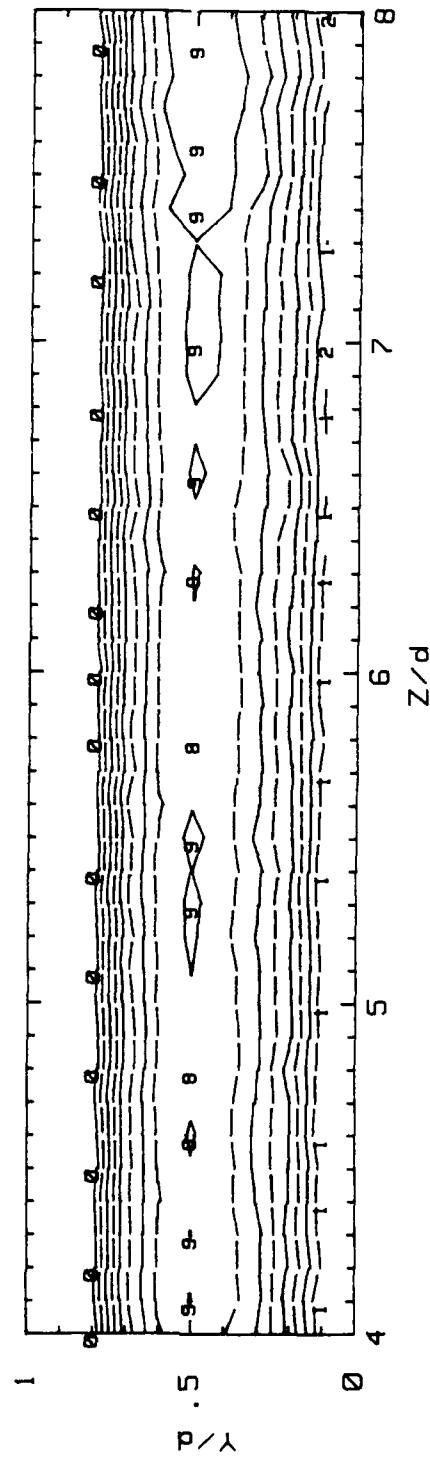


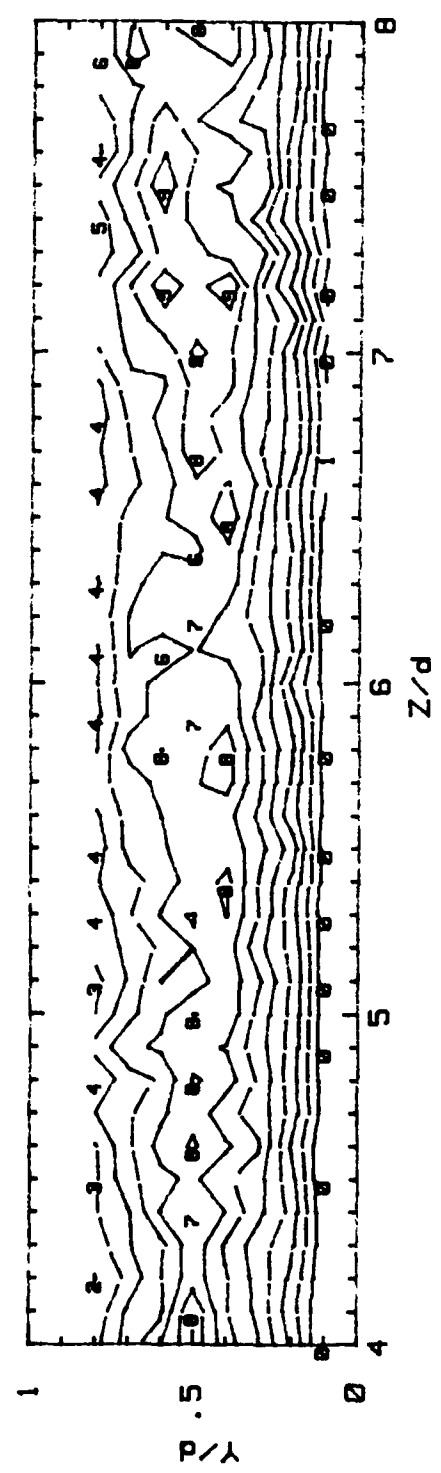
Figure 89. Streamwise Mean Velocity Contour,  $De=451.5$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = .42 \text{ m/s}$   $De = 50.16$   $Re = 343.9$

RUN 052391.2209



### $U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .00002 TO .00002	5: .00004 TO .00004
1: .00002 TO .00003	6: .00004 TO .00005
2: .00003 TO .00003	7: .00005 TO .00005
3: .00003 TO .00004	8: .00005 TO .00006
4: .00004 TO .00004	9: .00006 TO .00006

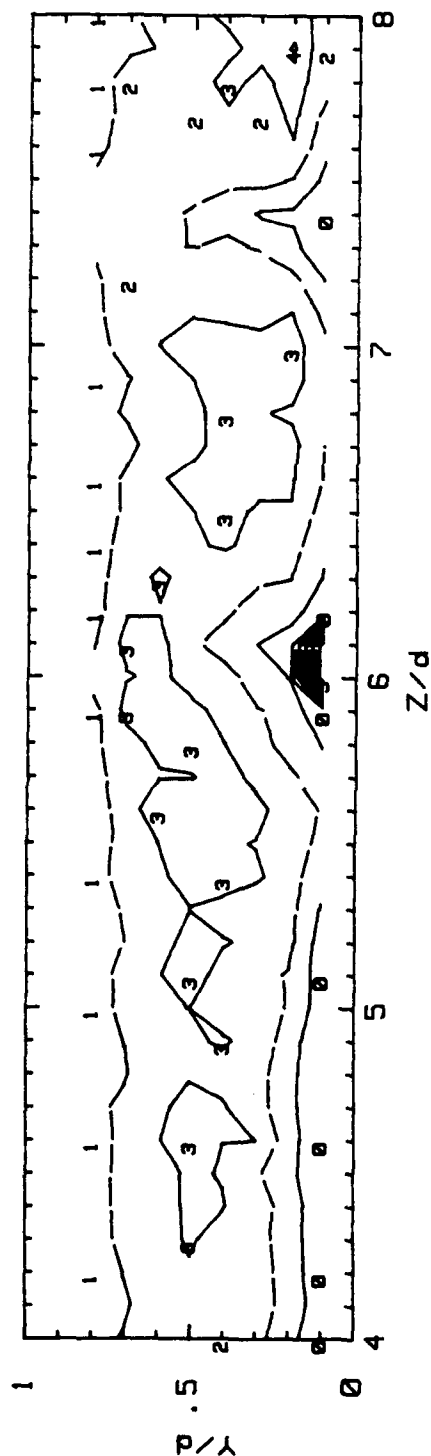
Figure 90. Longitudinal Reynolds Normal Stress Contour,  $De=50.2$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = .51 \text{ m/s}$   $De = 60.23$   $Re = 412.9$

RUN 052491.2201



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .00002 TO .00003	5: .00009 TO .00010
1: .00003 TO .00005	6: .00010 TO .00011
2: .00005 TO .00006	7: .00011 TO .00013
3: .00006 TO .00007	8: .00013 TO .00014
4: .00007 TO .00009	9: .00014 TO .00015

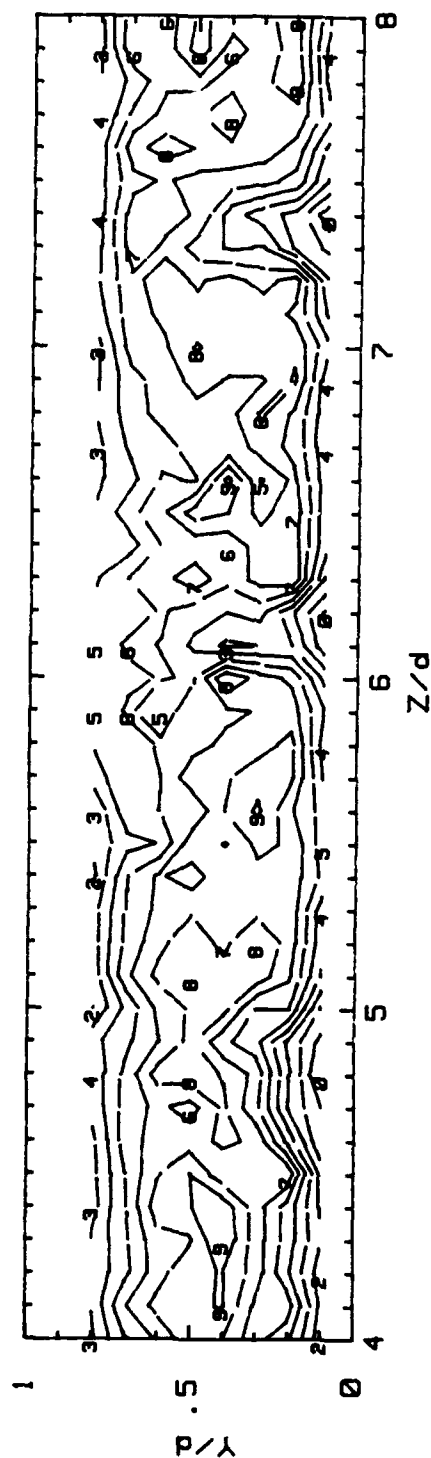
Figure 91. Longitudinal Reynolds Normal Stress Contour,  $De=60.2$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = .59 \text{ m/s}$   $De = 70.22$   $Re = 481.4$

RUN 052591.2211



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .00002 TO .00002	5: .00005 TO .00006
1: .00002 TO .00003	6: .00006 TO .00006
2: .00003 TO .00004	7: .00006 TO .00007
3: .00004 TO .00004	8: .00007 TO .00007
4: .00004 TO .00005	9: .00007 TO .00008

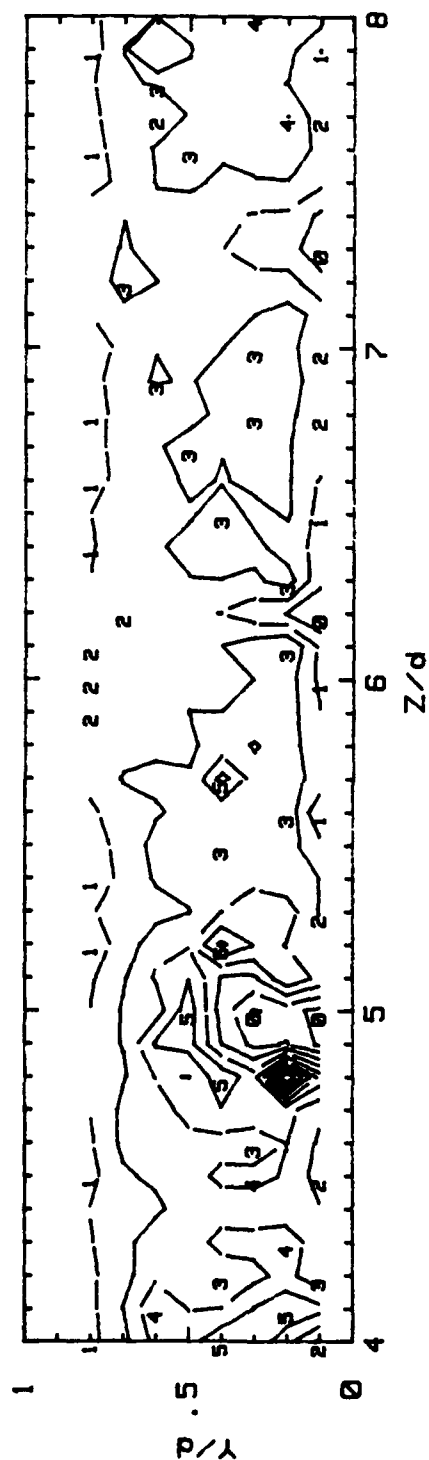
Figure 92. Longitudinal Reynolds Normal Stress Contour,  $De=70.2$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

Ubulk = .67 m/s De = 80.31 Re = 550.6

RUN 052691.2225



U'^2 (m^2/s^2) RANGES

0:	.00002 TO .00004	5:	.00010 TO .00012
1:	.00004 TO .00005	6:	.00012 TO .00013
2:	.00005 TO .00007	7:	.00013 TO .00015
3:	.00007 TO .00009	8:	.00015 TO .00017
4:	.00009 TO .00010	9:	.00017 TO .00018

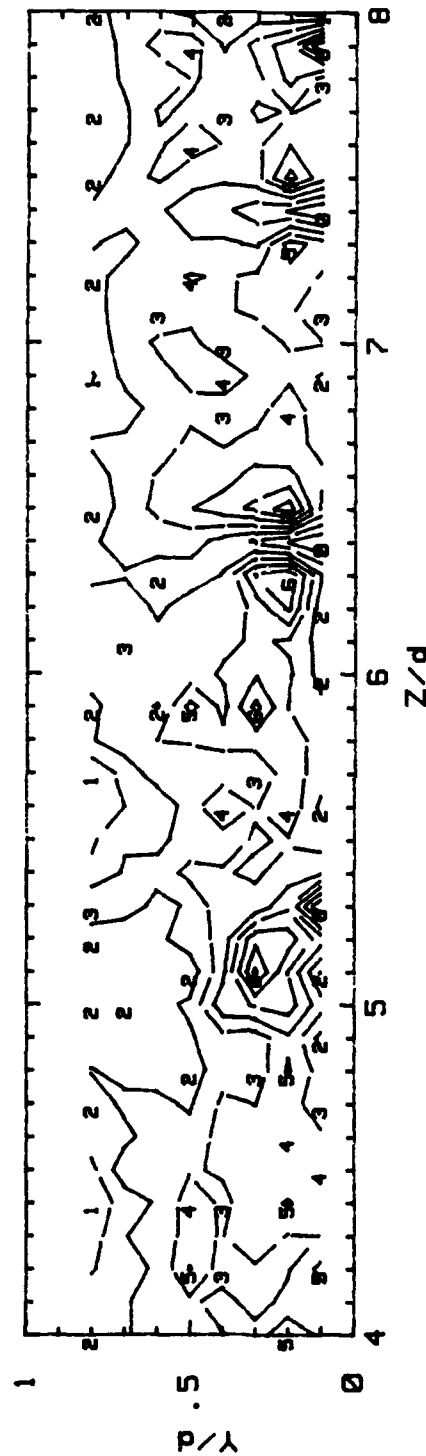
Figure 93. Longitudinal Reynolds Normal Stress Contour, De=80.3

# Longitudinal Reynolds Stress

## CURVED CHANNEL

Ubulk = .76 m/s De = 90.36 Re = 619.5

RUN 052791.2211



U'^2 (m^2/s^2) RANGES

0: .00003 TO .00004	5: .00011 TO .00012
1: .00004 TO .00006	6: .00012 TO .00014
2: .00006 TO .00007	7: .00014 TO .00015
3: .00007 TO .00009	8: .00015 TO .00017
4: .00009 TO .00011	9: .00017 TO .00019

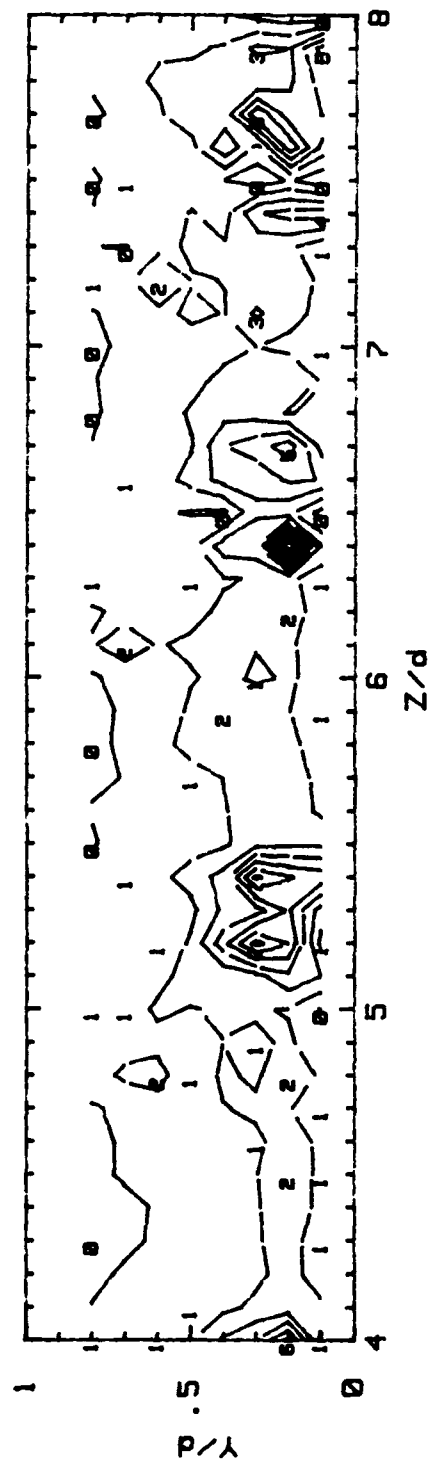
Figure 94. Longitudinal Reynolds Normal Stress Contour, De=90.4

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = .84 \text{ m/s}$   $De = 100.4$   $Re = 688.1$

RUN 052891.2157



### $U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .00004 TO .00007	5: .00019 TO .00022
1: .00007 TO .00010	6: .00022 TO .00025
2: .00010 TO .00013	7: .00025 TO .00028
3: .00013 TO .00016	8: .00028 TO .00031
4: .00016 TO .00019	9: .00031 TO .00034

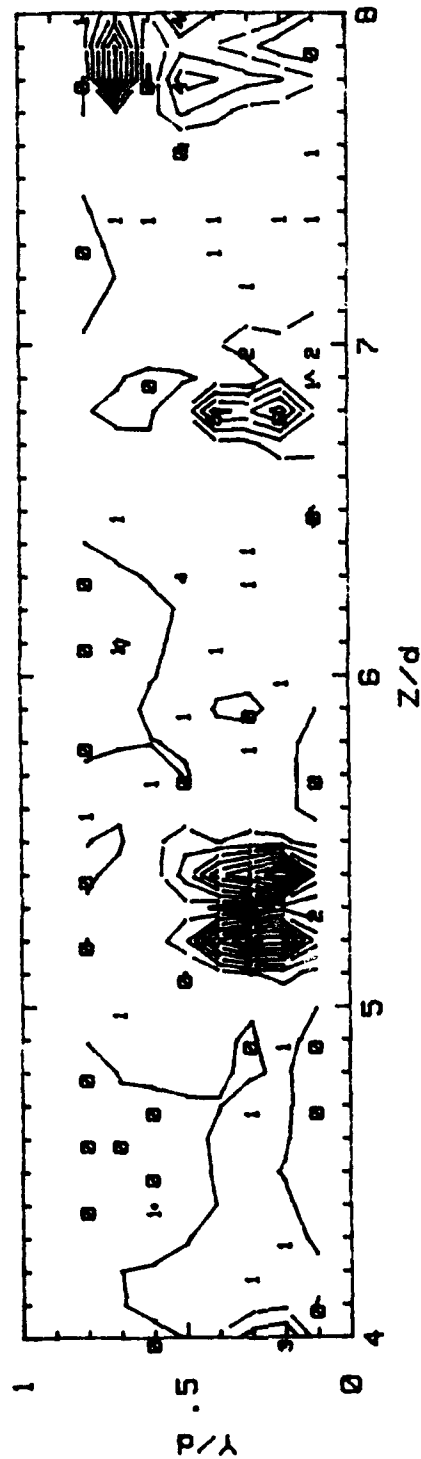
Figure 95. Longitudinal Reynolds Normal Stress Contour,  $De=100.4$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 1.1 \text{ m/s}$   $De = 125.4$   $Re = 859.9$

RUN 053091.2157



### $U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0:	.00004	TO	.00012	5:	.00043	TO	.00051
1:	.00012	TO	.00020	6:	.00051	TO	.00058
2:	.00020	TO	.00027	7:	.00058	TO	.00066
3:	.00027	TO	.00035	8:	.00066	TO	.00074
4:	.00035	TO	.00043	9:	.00074	TO	.00082

Figure 96. Longitudinal Reynolds Normal Stress Contour,  $De=125.4$

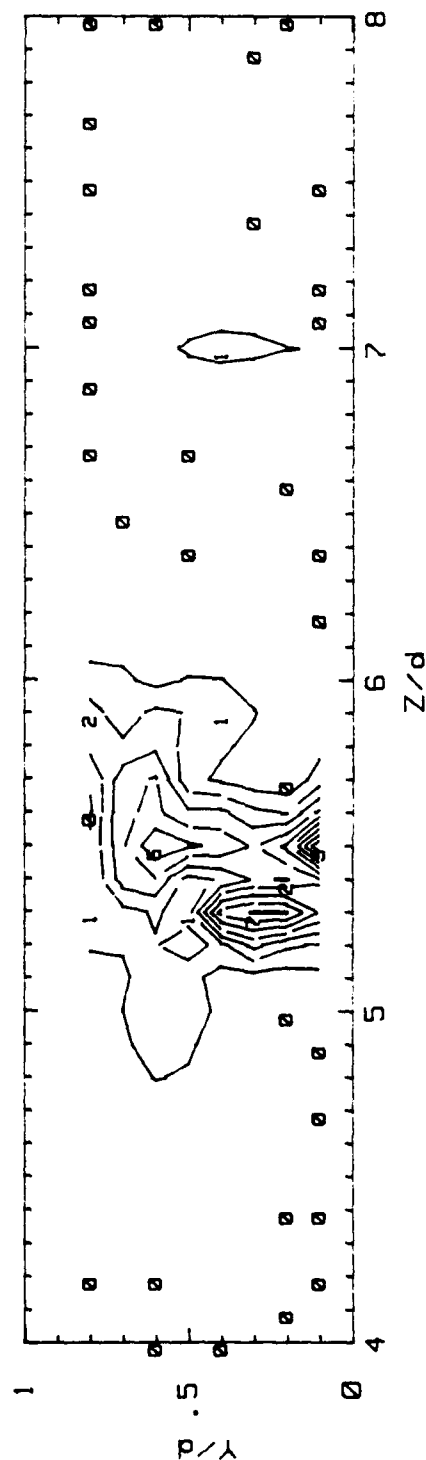


# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 1.3 \text{ m/s}$   $De = 150.6$   $Re = 1032$

RUN 053191.2201



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0:	.00011	TO	.00348	5:	.01700	TO	.02030
1:	.00348	TO	.00686	6:	.02030	TO	.02370
2:	.00686	TO	.01020	7:	.02370	TO	.02710
3:	.01020	TO	.01360	8:	.02710	TO	.03050
4:	.01360	TO	.01700	9:	.03050	TO	.03380

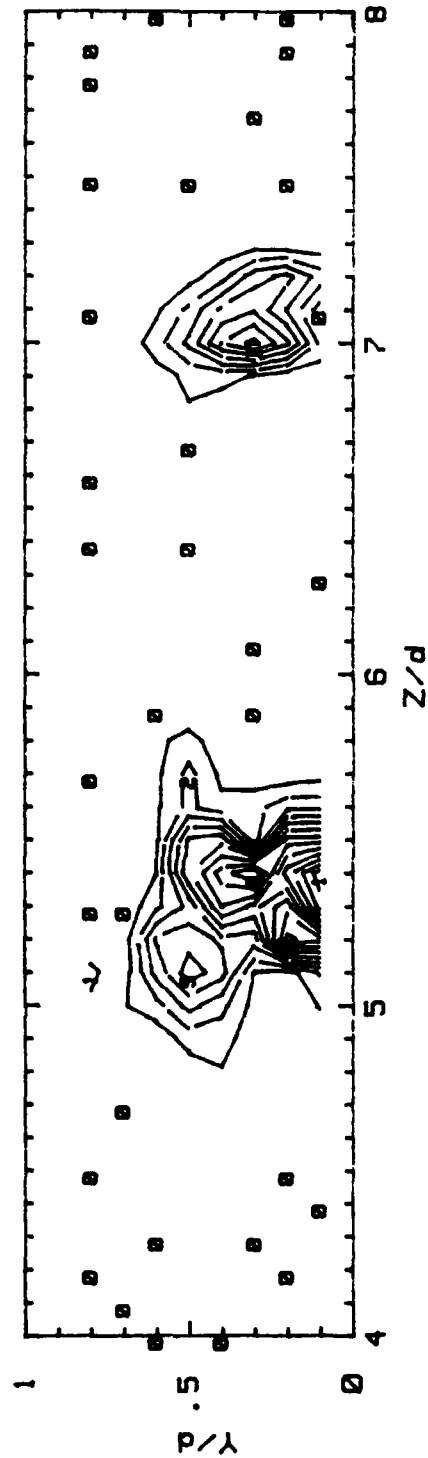
Figure 97. Longitudinal Reynolds Normal Stress Contour,  $De=150.6$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 1.3 \text{ m/s}$   $De = 160.5$   $Re = 1101$

RUN 052991.2155



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .00013 TO .00227	5: .01090 TO .01300
1: .00227 TO .00442	6: .01300 TO .01520
2: .00442 TO .00657	7: .01520 TO .01730
3: .00657 TO .00871	8: .01730 TO .01950
4: .00871 TO .01090	9: .01950 TO .02160

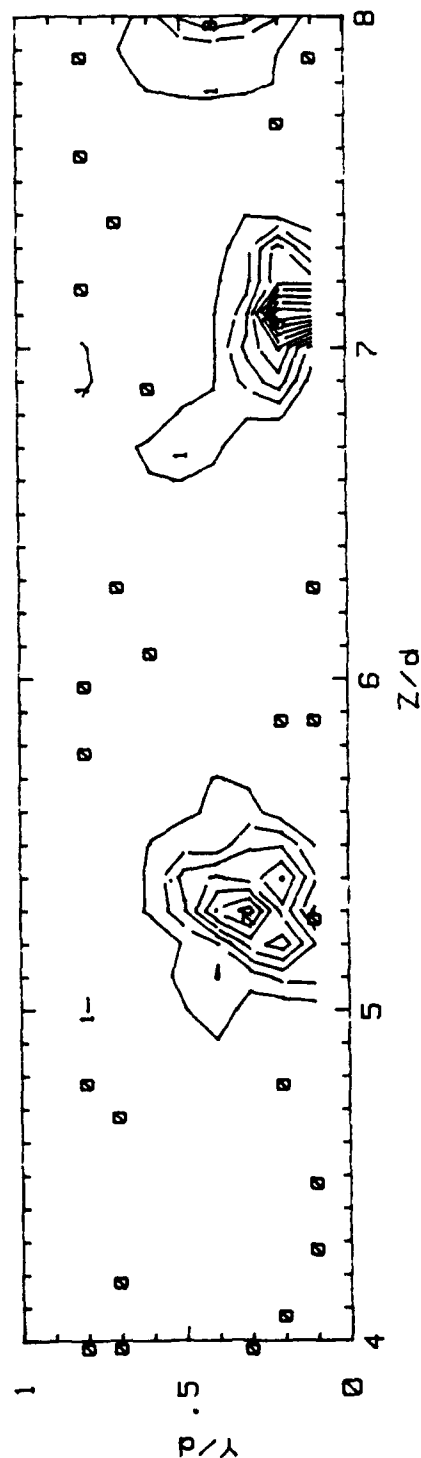
Figure 98. Longitudinal Reynolds Normal Stress Contour,  $De=160.5$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 1.4 \text{ m/s}$   $De = 170.6$   $Re = 1170$

RUN 060191.2157



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0:	.00017	TO	.00372	5:	.01790	TO	.02150
1:	.00372	TO	.00727	6:	.02150	TO	.02500
2:	.00727	TO	.01080	7:	.02500	TO	.02850
3:	.01080	TO	.01440	8:	.02850	TO	.03210
4:	.01440	TO	.01790	9:	.03210	TO	.03560

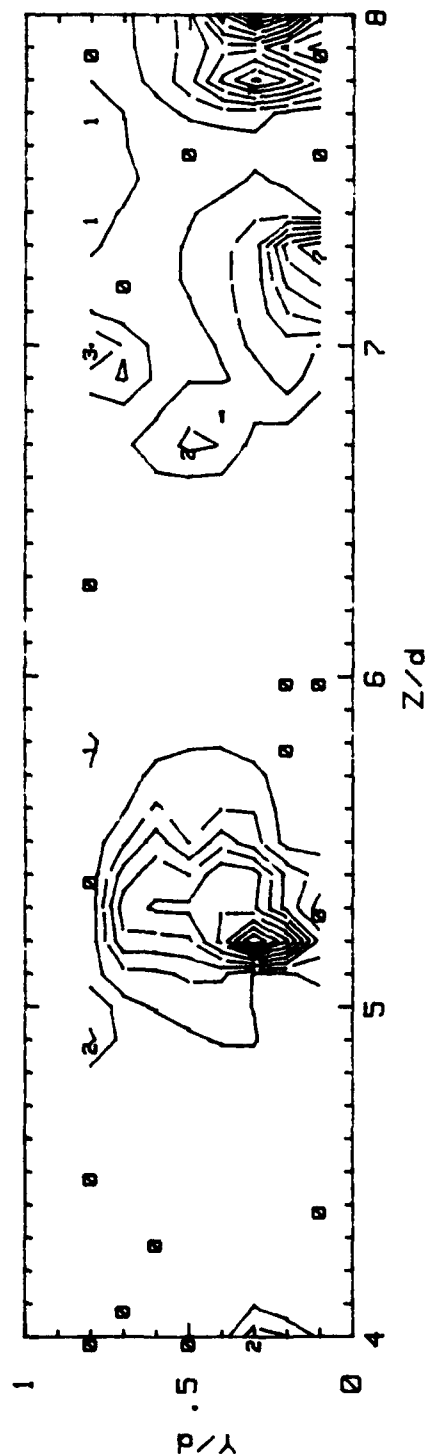
Figure 99. Longitudinal Reynolds Normal Stress Contour,  $De=170.6$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 1.5 \text{ m/s}$   $De = 180.7$   $Re = 1239$

RUN 060291.2151



## $U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .00024 TO .00321	5: .01510 TO .01810
1: .00321 TO .00619	6: .01810 TO .02110
2: .00619 TO .00916	7: .02110 TO .02400
3: .00916 TO .01210	8: .02400 TO .02700
4: .01210 TO .01510	9: .02700 TO .03000

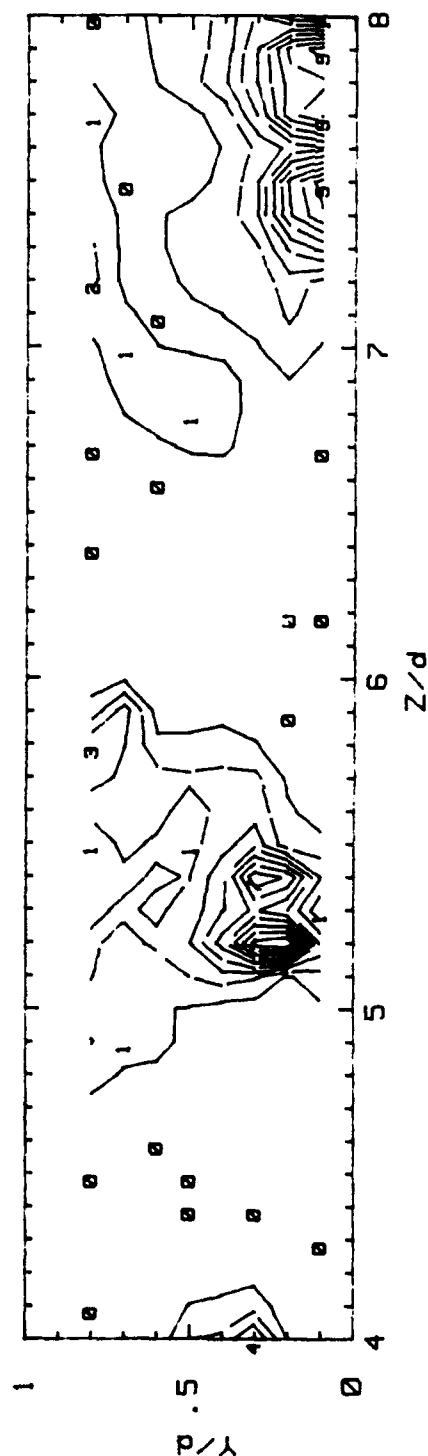
Figure 100. Longitudinal Reynolds Normal Stress Contour,  $De=180.7$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 1.6 \text{ m/s}$   $De = 190.7$   $Re = 1307$

RUN 060391.2156



### $U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .00023 TO .00320	5: .01510 TO .01810
1: .00320 TO .00617	6: .01810 TO .02100
2: .00617 TO .00914	7: .02100 TO .02400
3: .00914 TO .01210	8: .02400 TO .02700
4: .01210 TO .01510	9: .02700 TO .02990

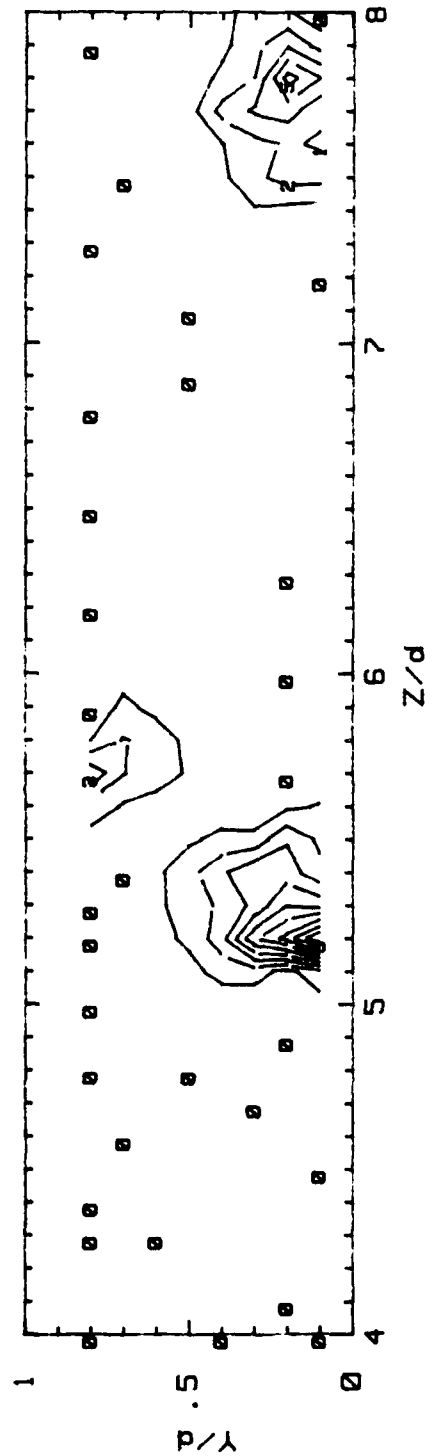
Figure 101. Longitudinal Reynolds Normal Stress Contour,  $De=190.7$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 1.7 \text{ m/s}$   $De = 200.7$   $Re = 1376$

RUN 060491.2207



### $U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .00034 TO .00859	5: .04160 TO .04990
1: .00859 TO .01680	6: .04990 TO .05810
2: .01680 TO .02510	7: .05810 TO .06640
3: .02510 TO .03330	8: .06640 TO .07460
4: .03330 TO .04160	9: .07460 TO .08290

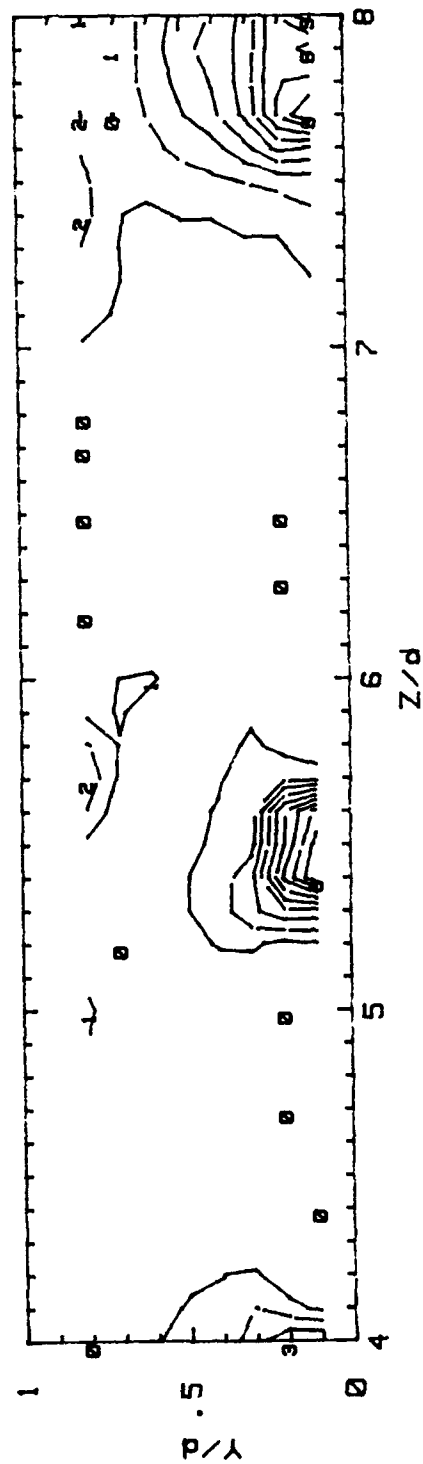
Figure 102. Longitudinal Reynolds Normal Stress Contour,  $De=200.7$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 1.9 \text{ m/s}$   $De = 225.7$   $Re = 1548$

RUN 060591.2211



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .00069 TO .00999	5: .04720 TO .05650
1: .00999 TO .01930	6: .05650 TO .06580
2: .01930 TO .02860	7: .06580 TO .07510
3: .02860 TO .03790	8: .07510 TO .08450
4: .03790 TO .04720	9: .08450 TO .09380

Figure 103. Longitudinal Reynolds Normal Stress Contour,  $De=225.7$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 1.9 \text{ m/s}$   $De = 230.8$   $Re = 1582$

RUN 060691.2205

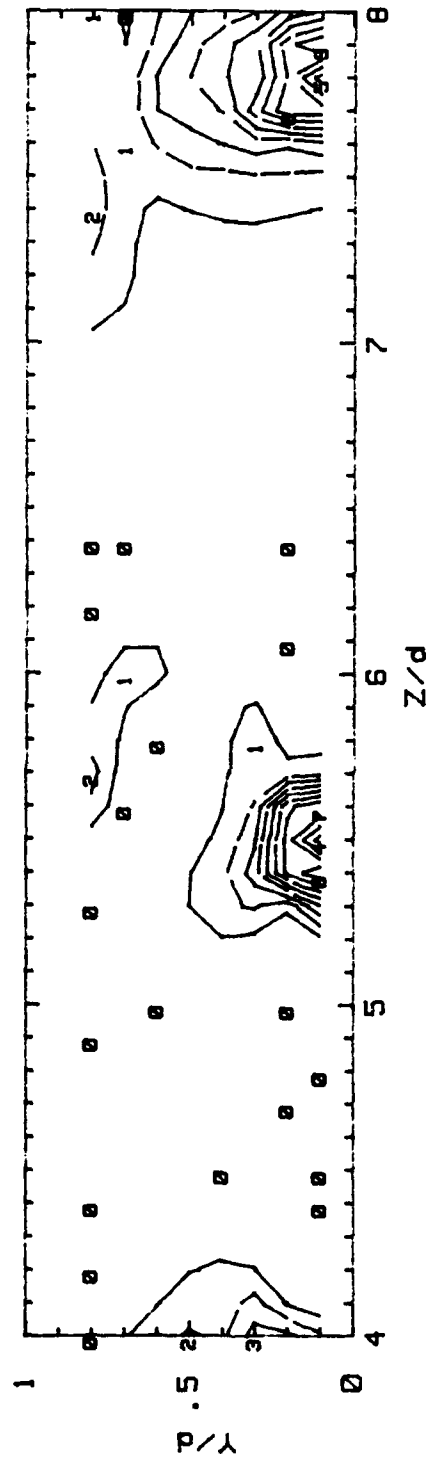


Figure 104. Longitudinal Reynolds Normal Stress Contour,  $De=230.8$

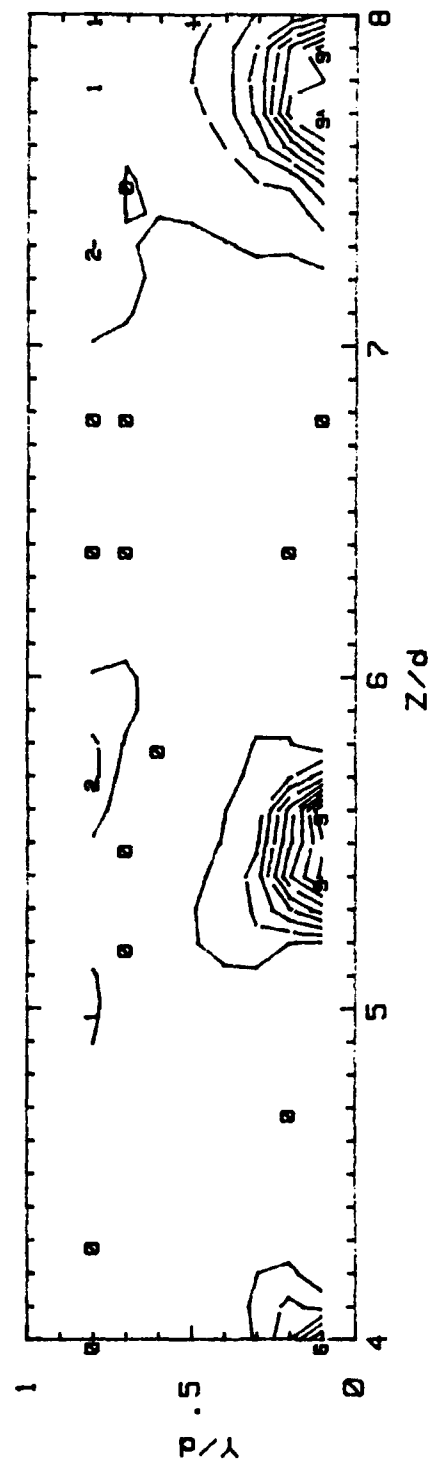


# Longitudinal Reynolds Stress

## CURVED CHANNEL

Ubulk = 2 m/s De = 240.8 Re = 1651

RUN 060791.2159



$U'^2$  ( $m^2/s^2$ ) RANGES

0:	.00092	TO	.01080		5:	.05040	TO	.06030
1:	.01080	TO	.02070		6:	.06030	TO	.07020
2:	.02070	TO	.03060		7:	.07020	TO	.08010
3:	.03060	TO	.04050		8:	.08010	TO	.09000
4:	.04050	TO	.05040		9:	.09000	TO	.10000

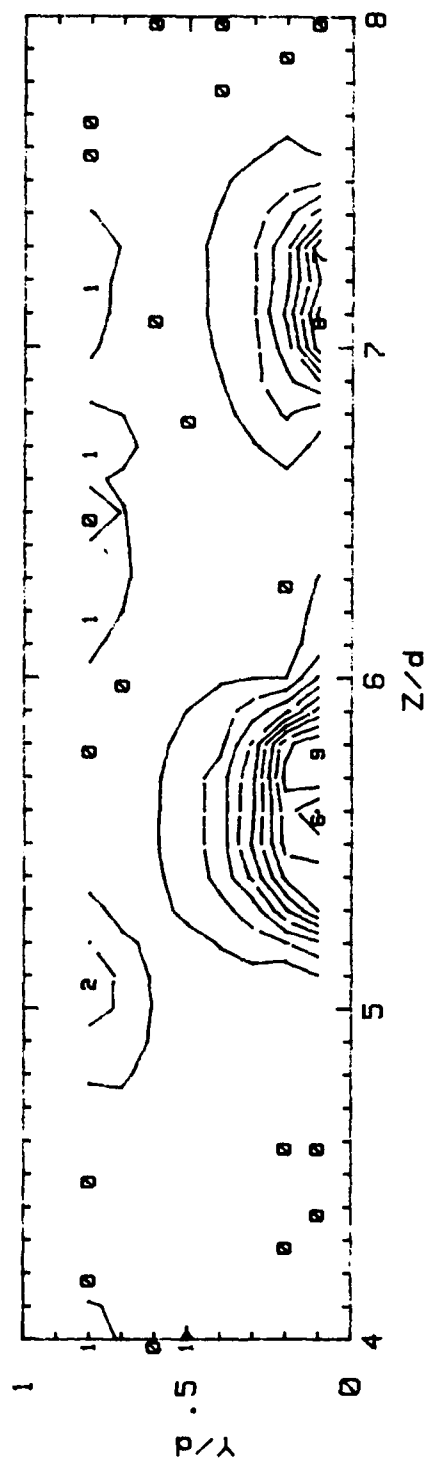
Figure 105. Longitudinal Reynolds Normal Stress Contour,  $De=240.8$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 2.1 \text{ m/s}$   $De = 250.8$   $Re = 1719$

RUN 070391.2145



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

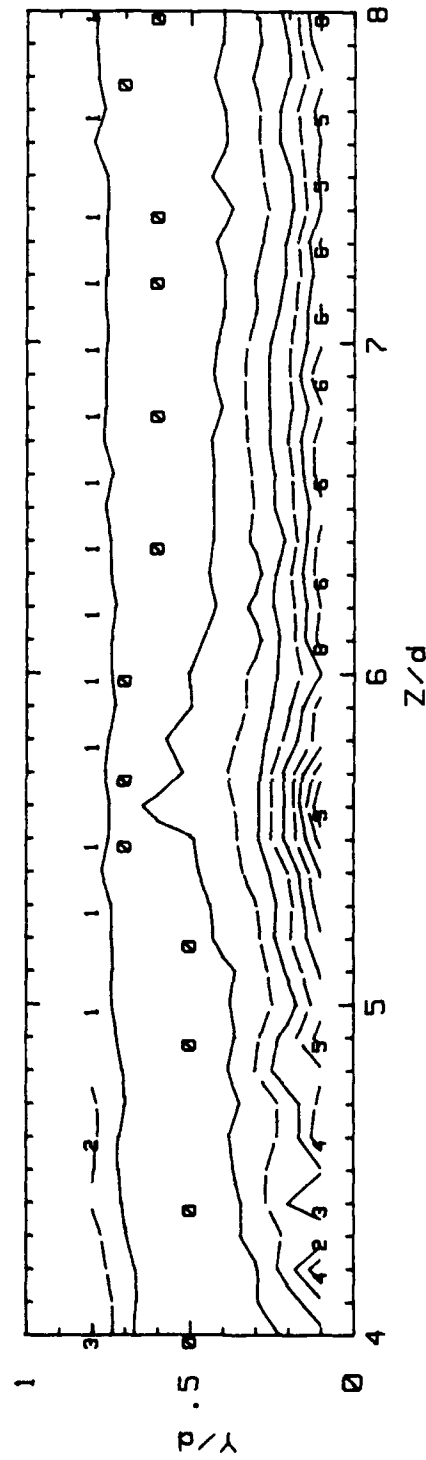
0:	.002 TO .020	5:	.092 TO .110
1:	.020 TO .038	6:	.110 TO .128
2:	.038 TO .056	7:	.128 TO .146
3:	.056 TO .074	8:	.146 TO .164
4:	.074 TO .092	9:	.164 TO .181

Figure 106. Longitudinal Reynolds Normal Stress Contour,  $De=250.8$

Longitudinal Reynolds Stress  
CURVED CHANNEL

$U_{bulk} = 2.2 \text{ m/s}$   $De = 263.3$   $Re = 1805$

RUN 070591.2201



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .023 TO .045	5: .134 TO .156
1: .045 TO .067	6: .156 TO .178
2: .067 TO .089	7: .178 TO .201
3: .089 TO .112	8: .201 TO .223
4: .112 TO .134	9: .223 TO .245

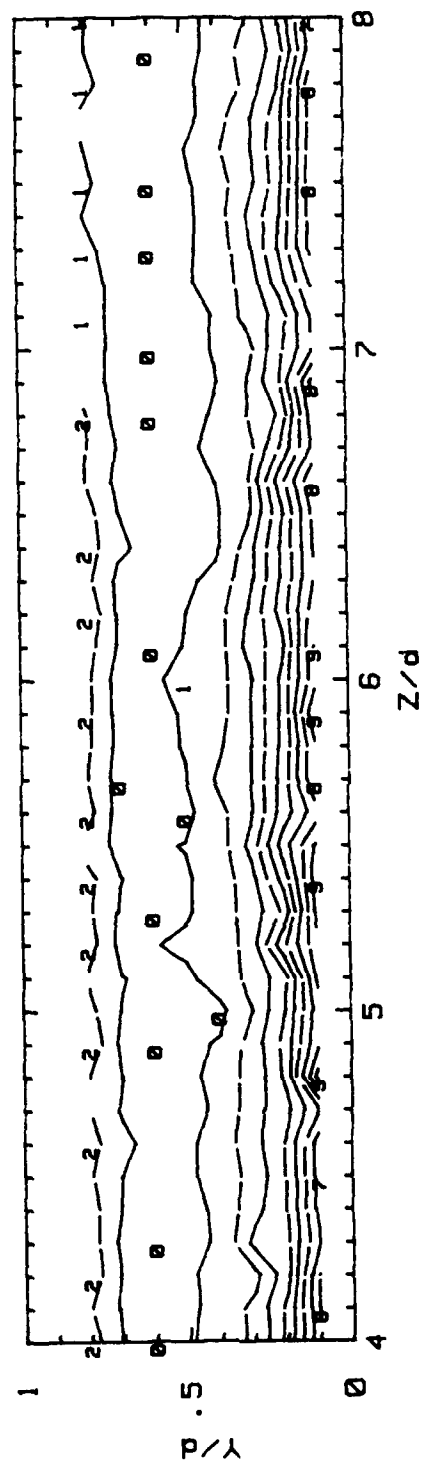
Figure 107. Longitudinal Reynolds Normal Stress Contour,  $De=263.3$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 2.3 \text{ m/s}$   $De = 275.9$   $Re = 1892$

RUN 070691.2155



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .021 TO .040	5: .113 TO .131
1: .040 TO .058	6: .131 TO .149
2: .058 TO .076	7: .149 TO .167
3: .076 TO .094	8: .167 TO .186
4: .094 TO .113	9: .186 TO .204

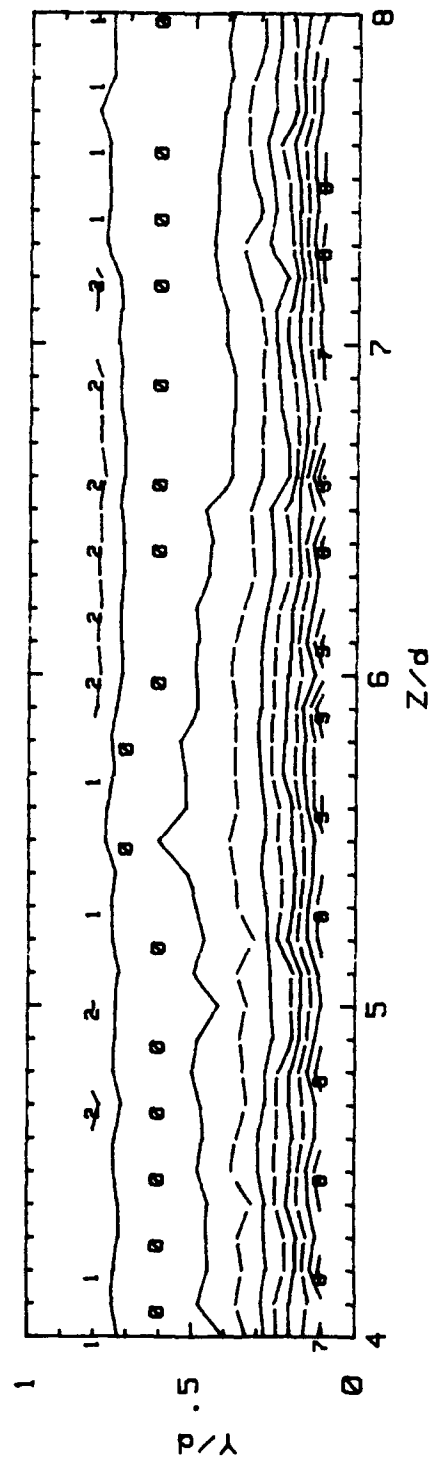
Figure 108. Longitudinal Reynolds Normal Stress Contour,  $De=275.9$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 2.5 \text{ m/s}$   $De = 301$   $Re = 2063$

RUN 070791.2154



### $U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .023 TO .046	5: .140 TO .163
1: .046 TO .070	6: .163 TO .187
2: .070 TO .093	7: .187 TO .210
3: .093 TO .116	8: .210 TO .234
4: .116 TO .140	9: .234 TO .257

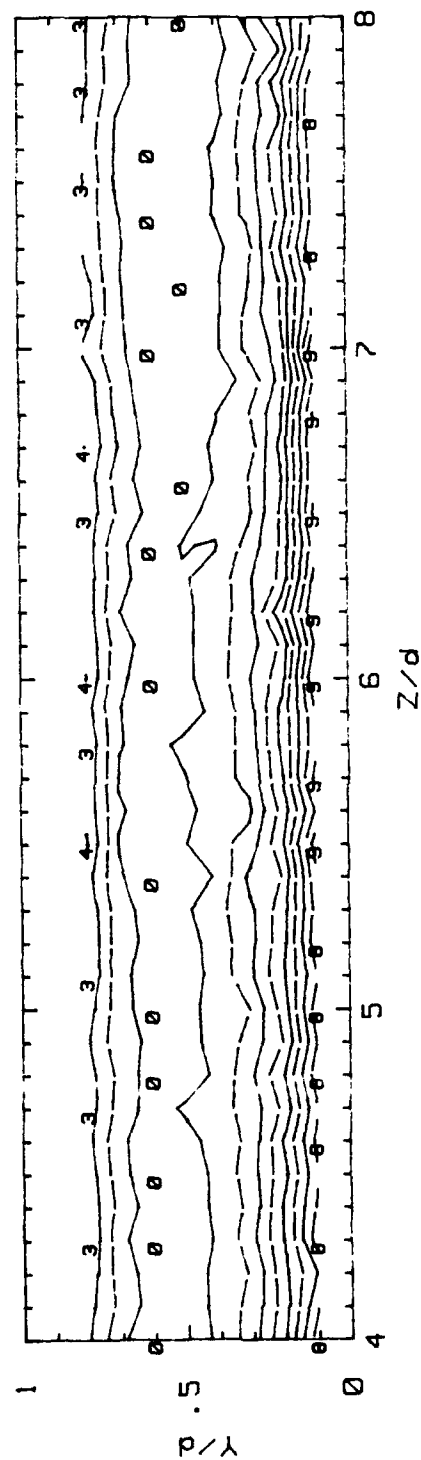
Figure 109. Longitudinal Reynolds Normal Stress Contour,  $De=301.1$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 2.7 \text{ m/s}$   $De = 326.1$   $Re = 2236$

RUN 071791.2157



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .034 TO .057	5: .151 TO .175
1: .057 TO .081	6: .175 TO .198
2: .081 TO .104	7: .198 TO .222
3: .104 TO .128	8: .222 TO .245
4: .128 TO .151	9: .245 TO .269

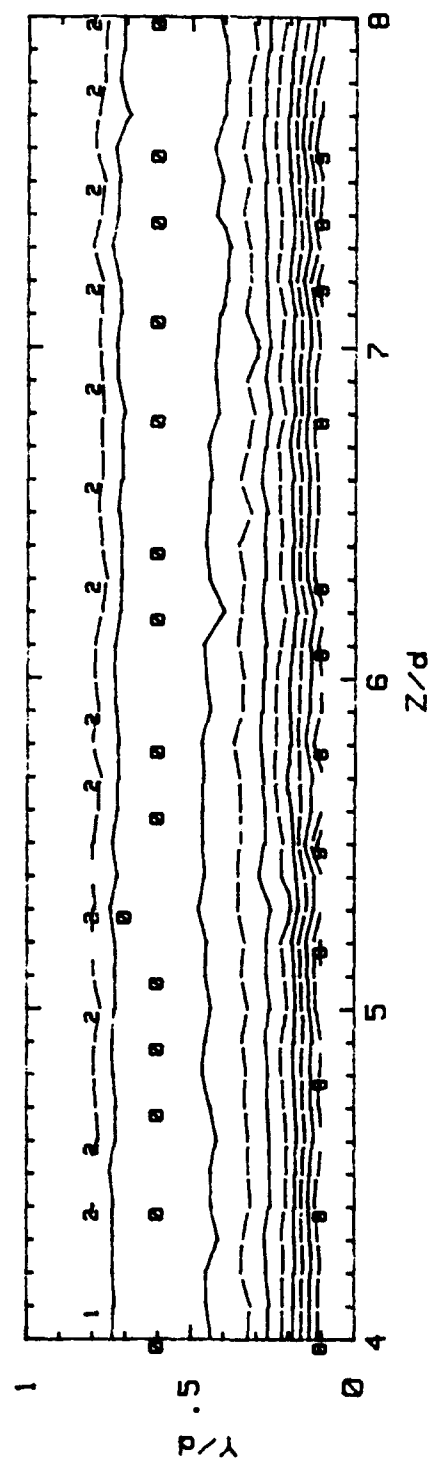
Figure 110. Longitudinal Reynolds Normal Stress Contour,  $De=326.1$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 2.9 \text{ m/s}$   $De = 351.1$   $Re = 2407$

RUN 070991.2135



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0:	.034 TO .060	5:	.163 TO .189
1:	.060 TO .086	6:	.189 TO .215
2:	.086 TO .112	7:	.215 TO .240
3:	.112 TO .137	8:	.240 TO .266
4:	.137 TO .163	9:	.266 TO .292

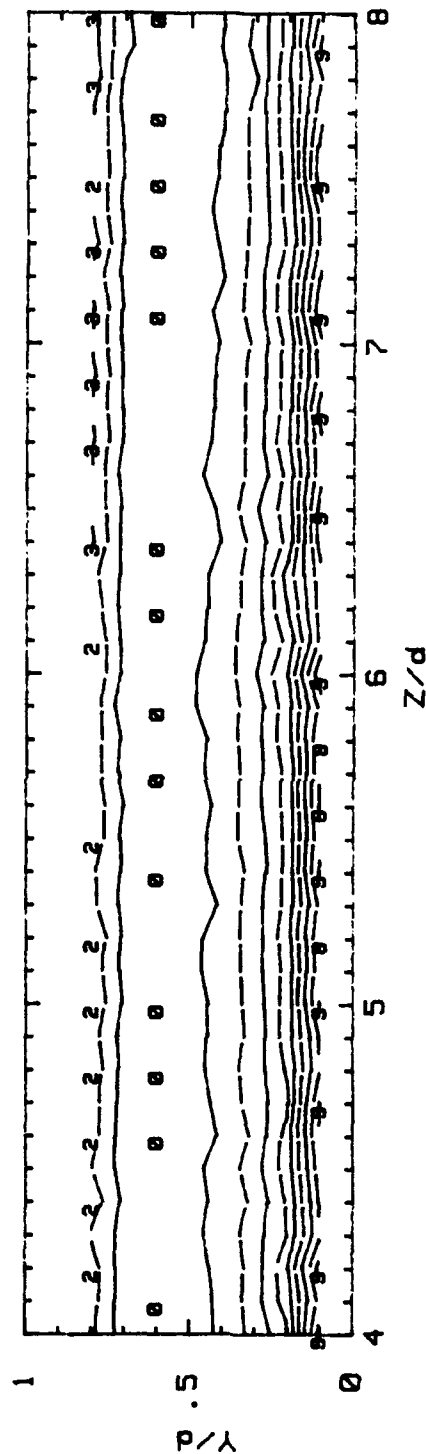
Figure 111. Longitudinal Reynolds Normal Stress Contour,  $De=351.1$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 3.2 \text{ m/s}$   $De = 376.2$   $Re = 2579$

RUN 071091.2151



## $U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .046 TO .076	5: .198 TO .228
1: .076 TO .107	6: .228 TO .258
2: .107 TO .137	7: .258 TO .288
3: .137 TO .167	8: .288 TO .319
4: .167 TO .198	9: .319 TO .349

Figure 112. Longitudinal Reynolds Normal Stress Contour,  $De=376.2$

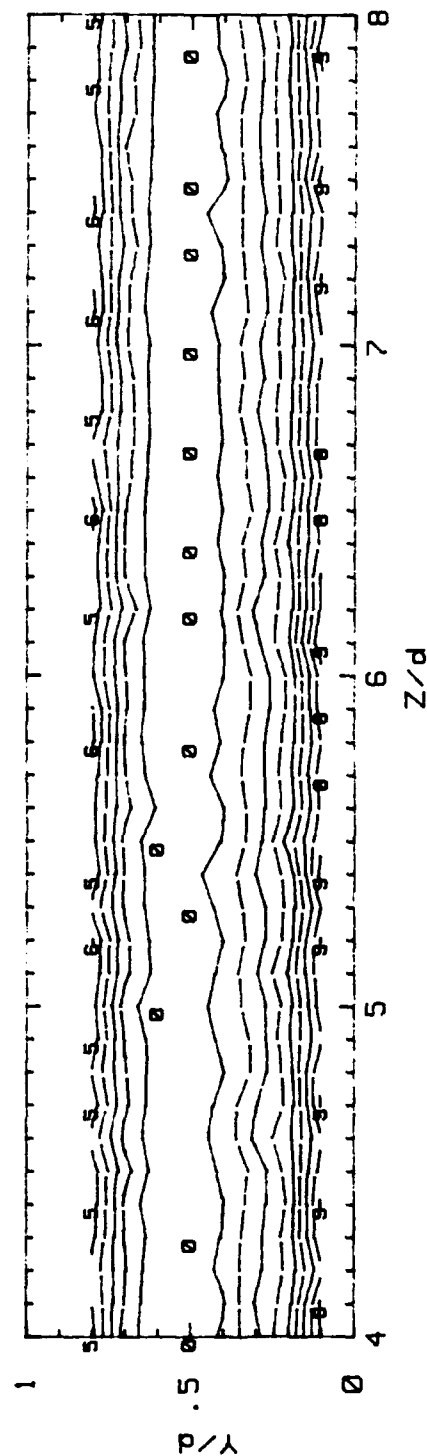


# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 3.4 \text{ m/s}$   $De = 401.3$   $Re = 2751$

RUN 071891.2201



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .063 TO .087	5: .184 TO .208
1: .087 TO .111	6: .208 TO .232
2: .111 TO .135	7: .232 TO .256
3: .135 TO .160	8: .256 TO .280
4: .160 TO .184	9: .280 TO .304

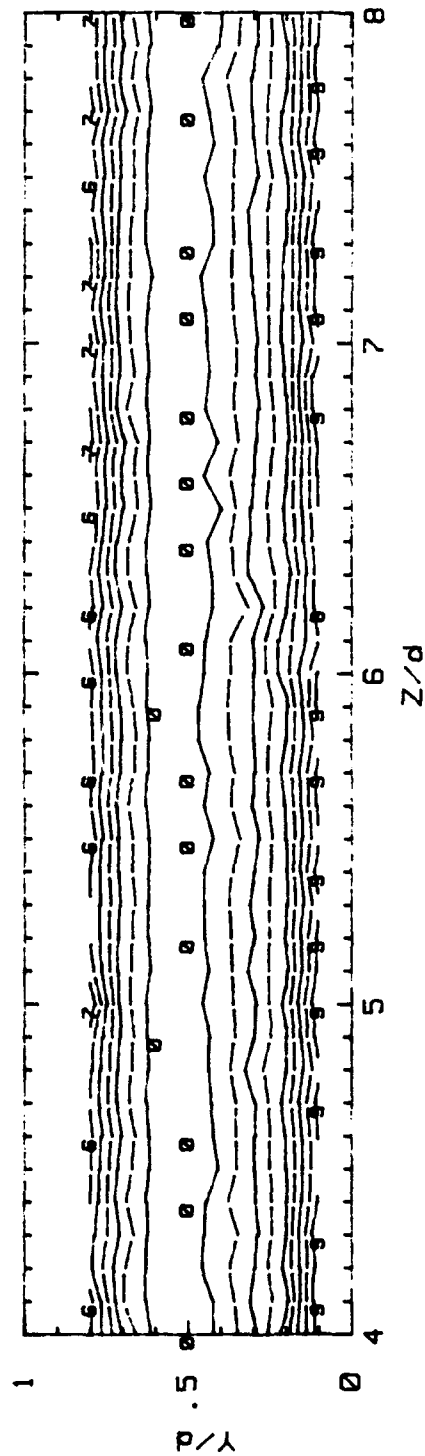
Figure 113. Longitudinal Reynolds Normal Stress Contour,  $De=401.3$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 3.6 \text{ m/s}$   $De = 426.4$   $Re = 2923$

RUN 071991.2202



## $U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .062 TO .084	5: .172 TO .194
1: .084 TO .106	6: .194 TO .216
2: .106 TO .128	7: .216 TO .238
3: .128 TO .150	8: .238 TO .260
4: .150 TO .172	9: .260 TO .282

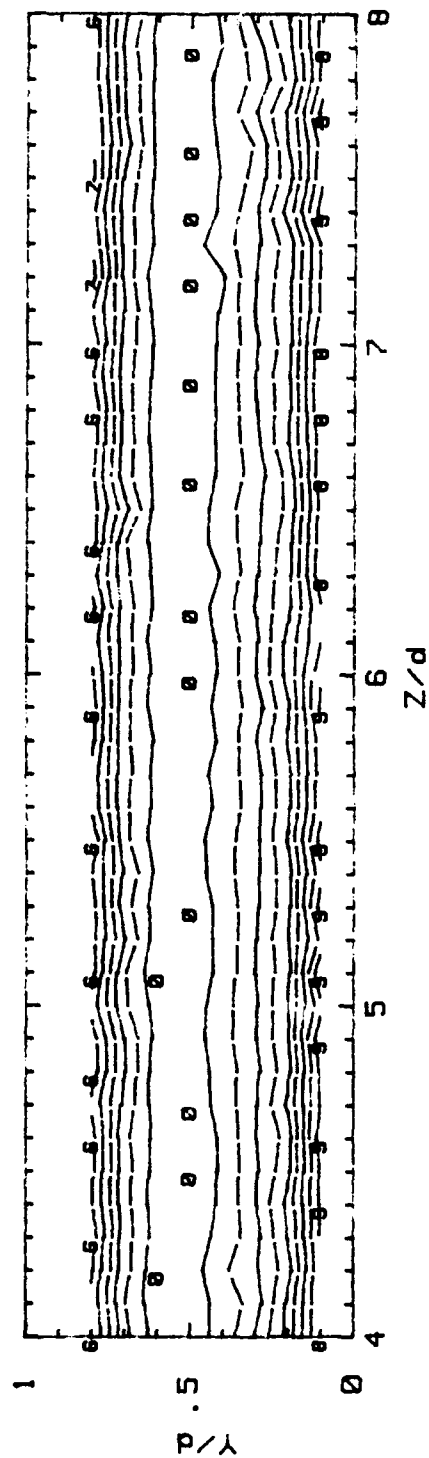
Figure 114. Longitudinal Reynolds Normal Stress Contour,  $De=426.4$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 3.8 \text{ m/s}$   $De = 451.5$   $Re = 3095$

RUN 072091.2201



### $U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .071 TO .097	5: .201 TO .227
1: .097 TO .123	6: .227 TO .254
2: .123 TO .149	7: .254 TO .280
3: .149 TO .175	8: .280 TO .306
4: .175 TO .201	9: .306 TO .332

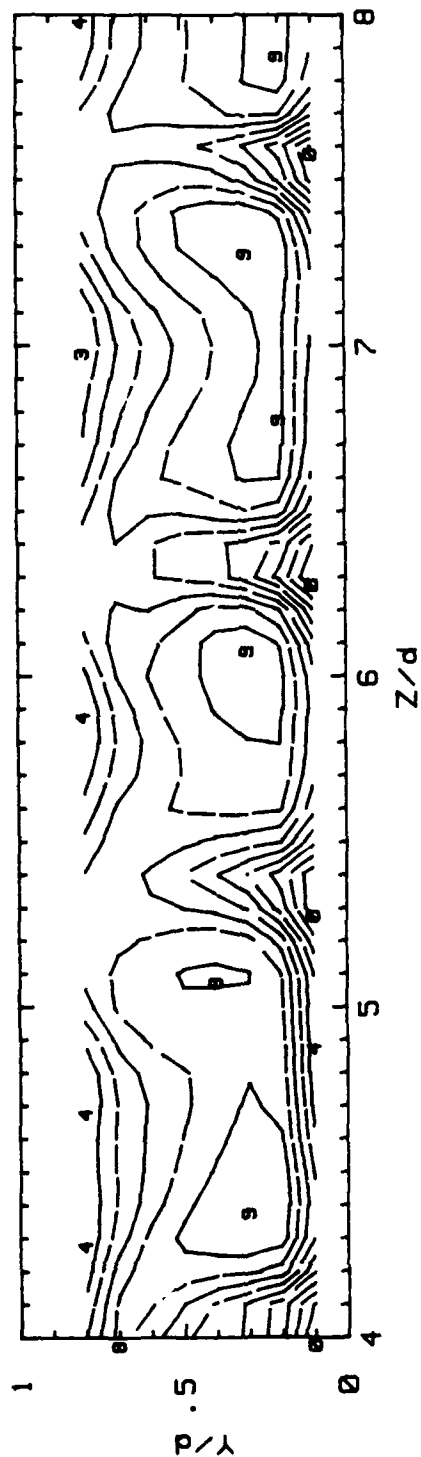
Figure 115. Longitudinal Reynolds Normal Stress Contour,  $De=451.5$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 1.1 \text{ m/s}$   $De = 125.4$   $Re = 859.9$

RUN 042191.2211



### U (m/s) RANGES

0: 0.47 TO 0.57	5: 0.97 TO 1.07
1: 0.57 TO 0.67	6: 1.07 TO 1.17
2: 0.67 TO 0.77	7: 1.17 TO 1.27
3: 0.77 TO 0.86	8: 1.27 TO 1.37
4: 0.86 TO 0.97	9: 1.37 TO 1.47

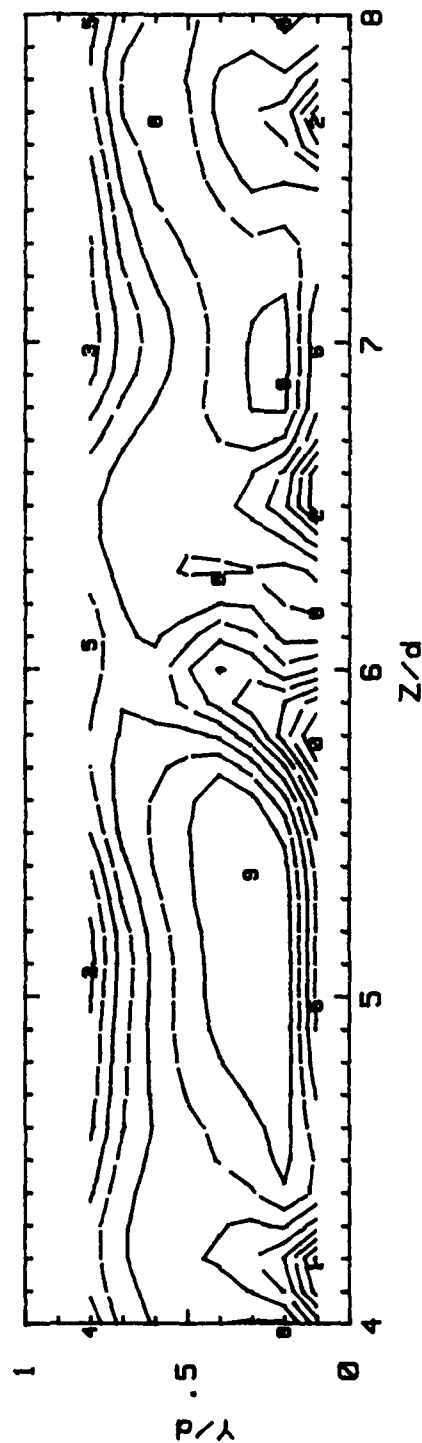
Figure 116. Streamwise Mean Velocity Contour (prior to channel cleaning),  $De=125.4$

# Streamwise Mean Velocity

## CURVED CHANNEL

$U_{bulk} = 1.5 \text{ m/s}$   $De = 175.6$   $Re = 1204$

RUN 042391.2137



## U (m/s) RANGES

0: 0.80 TO 0.93	5: 1.44 TO 1.57
1: 0.93 TO 1.06	6: 1.57 TO 1.70
2: 1.06 TO 1.18	7: 1.70 TO 1.82
3: 1.18 TO 1.31	8: 1.82 TO 1.95
4: 1.31 TO 1.44	9: 1.95 TO 2.08

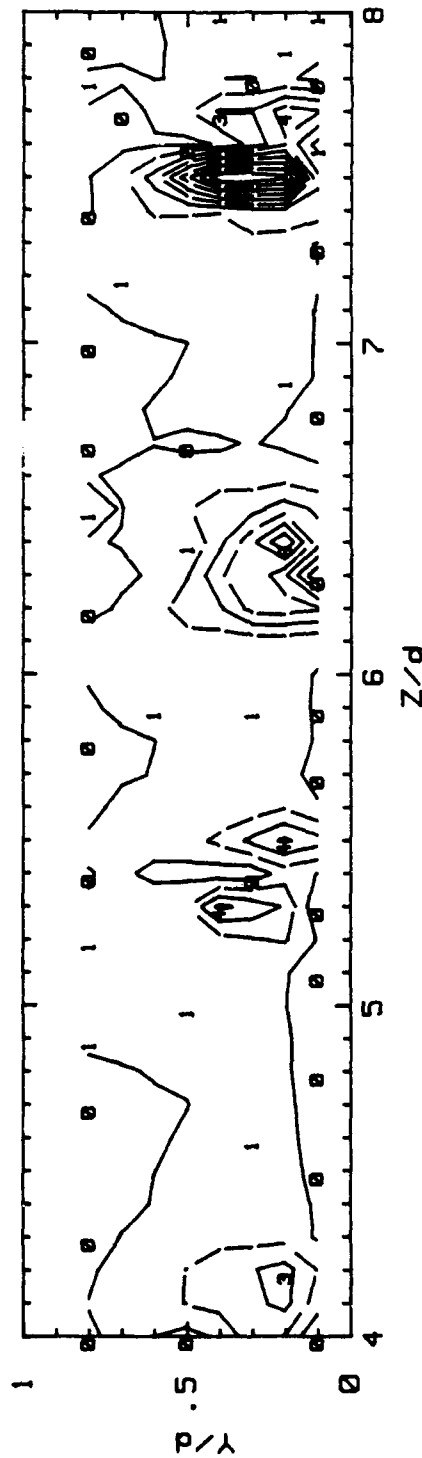
Figure 117. Streamwise Mean Velocity Contour (prior to channel cleaning),  $De=175.6$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

$U_{bulk} = 1.1 \text{ m/s}$   $De = 125.4$   $Re = 859.9$

RUN 042191.2211



$U'^2 \text{ (m}^2/\text{s}^2\text{) RANGES}$

0: .00045 TO .00081	5: .00229 TO .00266
1: .00081 TO .00118	6: .00266 TO .00303
2: .00118 TO .00155	7: .00303 TO .00340
3: .00155 TO .00192	8: .00340 TO .00376
4: .00192 TO .00229	9: .00376 TO .00413

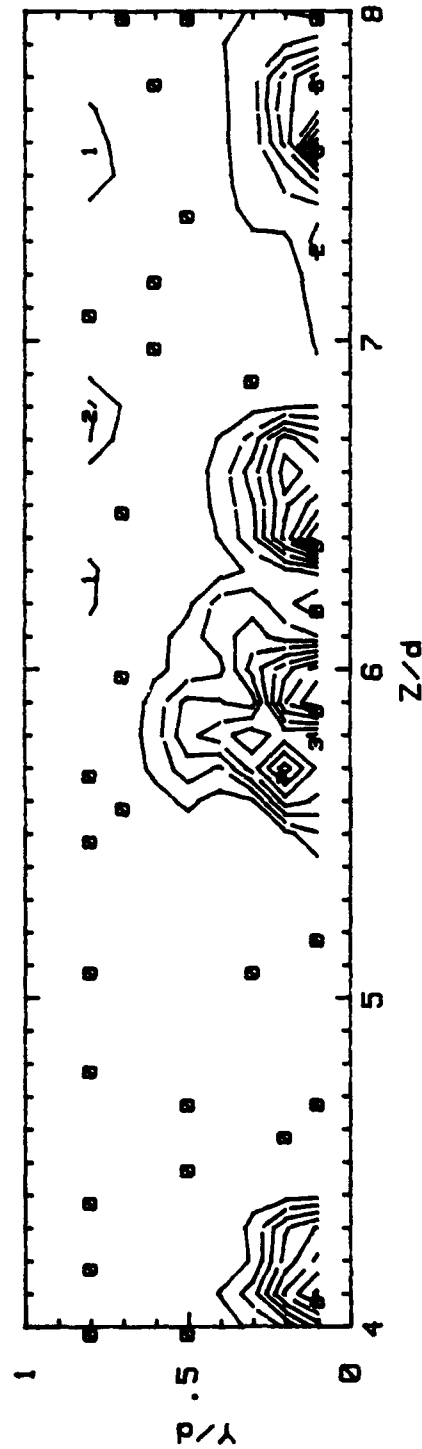
Figure 118. Longitudinal Reynolds Normal Stress Contour (prior to channel cleaning),  $De=125.4$

# Longitudinal Reynolds Stress

## CURVED CHANNEL

Ubulk = 1.5 m/s De = 175.6 Re = 1204

RUN 042391.2137



U'^2 (m^2/s^2) RANGES

0: .002 TO .012	5: .056 TO .067
1: .012 TO .023	6: .067 TO .077
2: .023 TO .034	7: .077 TO .088
3: .034 TO .045	8: .088 TO .099
4: .045 TO .056	9: .099 TO .110

Figure 119. Longitudinal Reynolds Normal Stress Contour (prior to channel cleaning), De=175.6

## APPENDIX B. SOFTWARE DIRECTORY

This appendix lists the various programs use in this study. Accompanying each program listed, is a general description the program . All programs are written/modified in BASIC 4.0 for use on the HP series 9000 model 310 computer unless mentioned otherwise. The programs are listed in order of usage.

<i>Program name</i>	<i>Description</i>
<b>HWCAL</b>	This program processes the data obtained during calibration of the single-sensor hot-wire probes. The program determines calibration constants that provide the best straight line fit through the data for $Re_d > 0.07$ . For $Re_d < 0.07$ , the constants needed in the third-order polynomial approximation previously discussed are determined. This program is written in FORTRAN-77 and was implemented on the Apple Macintosh SE computer.
<b>DEAN15M</b>	This program determines the Dean number in the curved channel based on the pressure drop across an ASME 1.5 inch orifice plate.
<b>TEMPMEAS</b>	This program calculates ambient temperatures at the channel inlet at 10 minute intervals. It requires input from a low-speed data acquisition system and a HP 300 9000 computer independent from that used for hot-wire data acquisition.
<b>HOTWIRE_u</b>	Data acquisition program for measurements in the spanwise/radial plane using single-sensor hot-wire probes. Measures actual system gain and offset, then constructs look-up table using probe calibration constants. The program includes commands to automatically move the probe through the desired number of grid locations at the desired grid spacing. Calculates stream wise mean velocity and longitudinal turbulence intensity at each grid location. The results are written to a data file specified by the user. Three versions of this program are available: 1) HOTWIREu_4 is used for surveys, 2) HOTWIREu_5 is used for profiles, and 3) HOTWIRESPl is used for inlet turbulence measurements [Ref. 7].



**DRFTCORC**

Data from HOTWIREu is corrected for temperature drift during collection of survey data. The program assumes a linear temperature variation during the run. The user must input the temperature at the start and at completion of the run.

**CCPF1M**

This program calculates the Curved Channel Poiseuille Flow (CCPF) and the maximum and minimum streamwise mean velocity at a given Dean number for Fields [Ref. 6] survey data. A second version, CCPF2M, is used for data from the present study. CCPF2M reads data files created by HOTWIREu.

**CONTOURS**

This program is a general purpose contour plotting program used to graphically present the data files created by HOTWIREu. The following plot types are available: streamwise mean velocity, streamwise mean velocity normalized by  $U_{bulk}$ , longitudinal turbulence intensity, longitudinal turbulence intensity normalized by local mean velocity squared, and longitudinal turbulence intensity normalized by  $U_{bulk}^2$ .

**3DPLOTS**

This program is similar to CONTOURS except that it plots up to seven plots on one page in a 3-D format. In addition to the five plot types available in CONTOURS, it will produce plots of  $u-u_{CCPF}$  and  $u_{CCPF}$ . When plotting  $u-u_{CCPF}$ , an option is available to determine the velocity perturbation,  $e$ .

## APPENDIX C. DATA DIRECTORY

This appendix lists the various program files and data files created during this study and their location. The program file names are logical and have been discussed in Appendix B. The data file names are in the following format: *TTNNN\_R*, where *TT* indicates the type of data (HW is used for survey data and NW is used for profile data), *NNN* indicates the nominal Dean number, and *R* indicates the run number for a given Dean number. This convention has been relaxed on disks 9 and 10 as this is the data actually used in producing the thesis plots presented in Appendix A.

<i>Disk name</i>	<i>File name</i>	<i>Remarks</i>
<b>PROGRAM DISK: 1</b>	CNT BUF AD DEAN15M HOTWIREu 4 HOTWIREu 5 CONTCURS PROFILES 3DPLOTS DRFTCORC	
<b>PROGRAM DISK: 2</b>	TEMPMEAS CCPF1M CCPF2M HOTWIRESPI	
<b>DATA DISK: 1</b>	HW050_1 HW100_0 HW050_2 HW075_1 HW100_1 HW200_1 HW125_1 HW150_1 HW175_1 HW225_1 HW250_1 HW150_2 HW250_2	

<i>Disk name</i>	<i>File name</i>	<i>Remarks</i>
<b>DATA DISK: 2</b>	HW250_3	
	HW150_3	
	HW250_4	
	HW275_1	
	HW275_2	
	HW300_1	
	HW325_1	
	HW350_1	
	HW375_1	
	HW400_1	
	HW425_1	
	HW450_1	
<b>DATA DISK: 3</b>	HW060_1	
	HW070_1	
	HW080_1	
	HW090_1	
	HW050_3	
	HW230_1	
	HW240_1	
	HW250_0	
	HW070_2	
	HW070_3	
	HW070_4	
<b>DATA DISK: 4</b>	HW075_2	
	HW075_3	
	HW075_4	
	HW050_4	
	HW050_5	(1)
	HW060_2	(1)
	HW070_5	(1)
	HW080_2	(1)
	HW090_2	(1)
	HW100_2	(1)
	HW160_1	(1)
	HW125_2	(1)
	HW150_4	(1)

<i>Disk name</i>	<i>File name</i>	<i>Remarks</i>
<b>DATA DISK: 5</b>	HW170_1	(1)
	HW180_1	(1)
	HW190_1	(1)
	HW200_2	(1)
	HW225_2	(1)
	HW230_2	(1)
	HW240_2	(1)
	HW250_6	
	HW275_3	
	HW300_2	
	HW325_2	
	HW350_2	
<b>DATA DISK: 6</b>	HW375_2	
	HW400_2	
	HW425_2	
	HW450_2	
	HW250_R	
	HW250_7	(1)
	HW262_1	(1)
	HW275_4	(1)
	HW300_3	(1)
	HW325_3	
	HW350_3	
	HW375_3	
	HW325_4	
<b>DATA DISK: 7</b>	HW400_3	
	HW425_3	
	HW450_3	
	HW325_5	
	HW325_6	
	HW400_4	
	HW425_4	
	HW450_4	
<b>DATA DISK: 8</b>	HW325_6TC	(1), (3)
	HW400_4TC	(1), (3)
	HW425_4TC	(1), (3)
	HW450_4TC	(1), (3)
	HW350_3TC	(1), (3)
	HW375_3TC	(1), (3)

<i>Disk name</i>	<i>File name</i>	<i>Remarks</i>
DATA DISK: 9	HW050	
	HW060	
	HW070	
	HW080	
	HW090	
	HW100	
	HW125	
	HW150	
	HW160	
	HW170	
	HW180	
	HW190	
	HW200	
DATA DISK: 10	HW225	
	HW230	
	HW240	
	HW250	
	HW262	
	HW275	
	HW300	
	HW325	
	HW350	
	HW375	
	HW400	
	HW425	
	HW450	
DATA DISK: 11	NW400_1	
	NW400_2	
	NW400_3	
	NW400_4	
	NW125_1	(2), $Z/d = 5.25$
	NW170_1	(2), $Z/d = 5.25$
	NW240_1	(2), $Z/d = 5.25$
	NW400_5	(2), $Z/d = 5.25$
	NW125_2	(2), $Z/d = 5.50$
	NW170_2	(2), $Z/d = 5.50$
	NW240_2	(2), $Z/d = 5.50$
	NW125_3	(2), $Z/d = 6.00$
	NW170_3	(2), $Z/d = 6.00$
	NW240_3	(2), $Z/d = 6.00$

**Remarks:** (1) This data is used in preparing thesis plots. The same data are stored using an abbreviated file name on data disks 9 and 10.

(2) This data is used in preparing thesis plots.

(3) This data has been corrected for variations in ambient temperature during the survey.

## LIST OF REFERENCES

1. Dean, W.R., "Fluid Motion in a Curved Channel," *Proceedings of The Royal Society of London, Series A*, v. 121, pp. 402-420, 01 November 1928.
2. Brewster, D.B., Grosberg, P. and Nissan, A.H., "The Stability of Viscous Flow Between Horizontal Concentric Cylinders," *Proceedings of The Royal Society of London, Series A*, v. 251, pp. 76-91, 15 September 1958.
3. Finlay, W.H., Keller, J.B., and Ferziger, J.H., "Finite Amplitude Vortices in Curved Channel Flow," *Journal of Fluid Mechanics*, v. 194, pp. 417-456, September 1988.
4. Ligrani, P.M., Niver, R.D., "Flow Visualization of Dean Vortices in a Curved Channel with 40 to 1 Aspect Ratio," *Physics of Fluids A*, v. 31, pp. 3605-3617, December 1988.
5. Kelleher, M.D., Flentie, D.L. and McKee, R.J., "An Experimental Study of the Secondary Flow in a Curved Rectangular Channel," *Fluids Engineering*, vol. 102, pp. 92-96, March 1980.
6. Matsson, O.J.E., and Alfredsson, P.H., "Curvature- and Rotation-induced Instabilities in Channel Flow," *Journal of Fluid Mechanics*, vol. 210, pp. 537-563, 1990.
7. Matsson, O.J.E., and Alfredsson, P.H., "Experiments on Instabilities in Curved Channel Flow," *Physic of Fluids A*, 1991.
8. Ligrani, P.M., Finlay, W.H., Fields, W.A., Fuqua, S.J., and Subramanian, C.S., "Features of Wavy Vortices in a Curved Channel from Experimental and Numerical Studies," *Physic of Fluids A*, 1991.
9. NASA Technical Memorandum 85974, *Direct Numerical Simulation of Curved Turbulent Channel Flow*, by R.D. Moser and P. Moin, October 1984.
10. Bottaro, A., Matsson, O.J.E., and Alfredsson, P.H., "Numerical and Experimental Results for Developing Curved Channel Flow," *Physics of Fluids A*, v. 3, p. 1473, 1991.
11. Niver, R.D., *Structural Characteristics of Dean Vortices in a Curved Channel*, M.S. Thesis, Naval Postgraduate School, Monterey, California, June 1987.
12. Baun, L.R., *The Development and Structural Characteristics of Dean Vortices in a Curved Rectangular Channel*, M.E. Thesis, Naval Postgraduate School, Monterey, California, September 1988.

13. Longest, J.M., *Flow Visualization Studies in (1) A Curved Rectangular Channel with 40 to 1 Aspect Ratio and (2) A Straight Channel with Bulk Flow Unsteadiness*, M.S. Thesis, Naval Postgraduate School, Monterey, California, June 1989.
14. Fields, W.A., *Study of the Effects of Centrifugal Instabilities on Flow in a 40 to 1 Aspect Ratio Rectangular Curved Channel, For Dean Numbers from 35 to Fully Turbulent Conditions*, M.E. Thesis, Naval Postgraduate School, Monterey, California, December 1990.
15. Kendall, M.R., *Effects of Centrifugal Instabilities on Laminar/Turbulent Transition in Curved Channels with 40 to 1 Aspect Ratios*, M.E. Thesis, Naval Postgraduate School, Monterey, California, June 1991.
16. Saric, W.A., conversation with P. Ligrani, May 1991.
17. Perry, A.E., *Hot-Wire Anemometry*, Clarendon Press, Oxford, 1982.
18. DISA, Probe Catalog, p. 10, 1989.
19. Ligrani, P.M. and Bradshaw, P., "Subminiature Hot-Wire Sensors: Development and Use," *Journal of Physics*, Vol. 20, pp. 323-332, 1987.
20. Green, J.G., *Turbulence Structure Resulting from Interaction Between an Embedded Vortex and Wall Jet*, M.S. Thesis, Naval Postgraduate School, Monterey, California, June 1989.
21. Baun, L.R., *The Development and Structural Characteristics of Dean Vortices in a Curved Rectangular Channel*, M.E. Thesis, Naval Postgraduate School, Monterey, California, September 1988.
22. Smith, B.J., *Study of Transition Phenomena in a Straight Channel With 40 to 1 Aspect Ratio With and Without Imposed Pulsations Part Two: Reynolds Number Surveys*, M.S. Thesis, Naval Postgraduate School, Monterey, California, March 1991.
23. Thermosciences Division, Department of Mechanical Engineering, Stanford University Report TF-30, *Instability and Transition in Curved Channel Flow*, by W.H. Finlay, J.B. Keller, and J.H. Ferziger, Stanford, California, May 1987.
24. Finlay, W.H., Keller, J.B. and Ferziger, J.H., "Finite Amplitude Vortices in Curved Channel Flow," *Journal of Fluid Mechanics*, v. 194, pp. 417-456, September 1988.
25. Clauser, F.H., "Turbulent Boundary Layers in Adverse Pressure Gradients," *Journal of the Aeronautical Sciences*, pp. 91-108, February 1954.
26. Kreplin, H. and Eckelmann, H., "Propagation of Perturbations in the Viscous Sublayer and Adjacent Wall Regions", *Journal of Fluid Mechanics*, v. 95, p. 305, 1979.



27. Morrow, D.S., *Transition Phenomena in a Straight Channel With a 40 to 1 Aspect Ratio With and Without Imposed Pulsations Part I: Near-Wall and Central Region Profiles*, M.S. Thesis, Naval Postgraduate School, Monterey, California, March 1991.

## INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center Cameron Station Alexandria, Virginia 22304-6145	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93943-5002	2
3.	Department Chairman, Code ME Department of Mechanical Engineering Naval Postgraduate School Monterey, California 93943-5000	1
4.	Naval Engineering Curricular Officer, Code ME Department of Mechanical Engineering Naval Postgraduate School Monterey, California 93943-5004	1
5.	Professor Phillip M. Ligrani Code ME/Li Department of Mechanical Engineering Naval Postgraduate School Monterey, California 93943-5000	3
6.	Professor Chelakara S. Subramanian Code ME/Su Department of Mechanical Engineering Naval Postgraduate School Monterey, California 93943-5000	2
7.	Dr. K.C. Civinskas Propulsion Directorate U.S. Army Aviation Research and Technology Activity AVSCOM NASA-Lewis Research Center Cleveland, Ohio 45433	2
8.	LT Steven J. Fuqua 20 Maid Marion Drive Gales Ferry, Connecticut 06335	2